The Syenite and Associated Rocks of the Mandamus-Pahau Area, North Canterbury, New Zealand

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Abstract

The intrusive rocks of the Mandamus-Pahau area consist of syenite and gabbro with associated sills of related composition. The rocks are distinctly alkaline in composition (alkali-lime index 52·5), which is shown by the presence of biotite and alkali feldspar in the gabbro and of alkaline pyroxenes and amphiboles in the syenite and trachytic rocks. It is believed that the syenitic rocks were derived by differentiation from the same magma as the gabbro. The syenite solidified under a comparatively thin cover, and gas pressure in the last stages of solidification was sufficient to shatter the roof of the intrusion, with the formation of an igneous breccia of fragments of roof rock and syenite in a trachytic matrix. The igneous rocks were probably intruded in the Lower Cretaceous, during the later stages of the Hokonui orogeny.

Introduction

Igneous activity accompanying the Hokonui orogeny was slight. Over the large areas of rocks which were deformed during this orogeny, both in the North Island and in the South Island, remarkably few occurrences of igneous rocks have been reported. Most of these are very minor, being narrow sills or dykes, and few have been accurately dated; some at least are probably of Tertiary age and unconnected with the Hokonui orogenic movements of early Cretaceous date.

It is on this account that the present study of the intrusive rocks of the Mandamus-Pahau district was undertaken. The occurrence of syenite intrusive into greywacke in this area has been known for many years, being first recorded in the literature by von Haast in 1871, and later mentioned by Hutton (1877) and Speight (1918). However, it has never been the subject of detailed investigation, although it is readily accessible and comparatively well exposed. I visited the district for the first time in 1936 and was impressed by the fine section through the syenite intrusion provided by the gorge of the Mandamus River. However, it was not until 1944 that I had the opportunity to examine it in detail. Field work was carried out intermittently between 1944 and 1947, and a general description of the geology of the area has recently been published (Mason, 1949). This paper describes in detail the igneous rocks and the problems which they pose.

The largest intrusion is the syenite, which forms a roughly oval mass about four miles long and up to a mile wide, extending along

[1] The field work was done while I was Lecturer in Geology at Canterbury University College. The laboratory investigation of the rocks was begun at that time, and was completed at Indiana University.

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the Hurunui Peak ridge nearly to the Hurunui River (Fig. 1). It is well exposed at many places, particularly in the gorge of the Mandamus River. Around Hurunui Peak itself an interesting igneous breccia is associated with the syenite. It is not separated from the syenite on the map illustrating this paper. About a mile to the north-east of the last outcrops of syenite a small area of gabbro is exposed in the bed of Hut Creek, a tributary of the Dove River. Associated with these plutonic rocks are a number of sills extending outwards from the plutonic bodies to distances of up to three miles. They are particularly well exposed in the Dove River and its tributaries, where they have been mapped in detail, and many were noted along the ridges, especially between the Dove and Glencoe rivers, and around the headwaters of Hut Creek and Cascade and Awatui streams; on the ridges and hill slopes, however, many such small intrusions were noted only from "float", and many more are doubtless concealed by the soil cover. For this reason the map does not give a true picture of the abundance of these sills, as only those whose outcrop could be located accurately are recorded thereon.

It should be mentioned here that a number of small sills and dykes intruding the greywacke crop out along the Pahau River east and north of this area. Although some of these may be connected with the intrusions described here, the majority appear to be distinct, and a cursory examination of their petrology and field relations suggests that some at least represent feeding channels of the basalts and agglomerates which form part of the Tertiary sequence.

DESCRIPTION OF THE ROCKS

A. *The syenite*

The syenite is the major igneous rock of the area. It forms the core of the Hurunui Peak ridge, which separates the valley of the Dove River from the Culverden depression, and extends across the Mandamus River nearly to the Hurunui River. Its outcrop is roughly oval, with a maximum length of four miles and a maximum width of half a mile. It is particularly well exposed in the gorge of the Mandamus River and that of Coal Creek, and crops out at many places along the hill slopes.

In hand specimen (Fig. 2) the syenite is a dull white rock speckled with irregular grains of dark green ferromagnesian minerals and sometimes with lustrous plates of black biotite. The rock is markedly porous even on superficial examination, with numerous angular cavities (sometimes partly filled with yellow-brown natrolite) between the feldspar laths. This porosity accounts for the friable nature of the rock in most outcrops; in many places the rock disintegrates into its individual mineral grains on rubbing between the hands, and looks more like a poorly consolidated sandstone than a plutonic rock. Fresh outcrops have a speckled black and white appearance, but where the rock has been subjected to weathering, the ferromagnesian minerals have been largely removed and the rock has a rusty-white colour; large weathered outcrops seen from a distance show a distinctly reddish colour which often serves to differentiate them from neighbouring outcrops of greywacke. The syenite varies little in grain size and texture over its whole area; no pegmatitic phases were seen, and the fine-grained selvages against the greywacke are never more than a few inches thick.

Under the microscope the feldspar is usually grey and turbid from beginning kaolinization. It is generally a fine-textured microperthite, although in some specimens the microperthite structure is scarcely detectible and the feldspar is best described as a cryptoperthite. The ferromagnesian minerals are aegirine, biotite and alkaline amphibole. Aegirine ($X \wedge c = 8°$) is the most abundant ferromagnesian mineral; sometimes the aegirine grains have a core of colourless or pale green augite. The biotite is very strongly pleochroic from yellow-brown to practically opaque. The alkaline amphibole is less common than the other ferromagnesian minerals and is absent from some thin sections; it often replaces pyroxene; it has extinction angle $Z \wedge c = 20°$ and pleochroism X = greenish-brown, Y = reddish-brown, Z = dark brown, and is probably barkevikite. In some specimens a little riebeckite was seen replacing aegirine. Accessory minerals are apatite in very small amount; black opaque material, probably magnetite; and rare euhedral titanite. A little natrolite occurs in the interstices of the feldspar laths A small amount of secondary calcite and a little opal is present in cavities. The mode of the analyzed specimen is given with the analysis (Table I).

Occasional variants of the syenite were found. One specimen collected from near the edge of the intrusion on the north side of Hurunui Peak was practically free from ferro-magnesian minerals and carried occasional grains ($< 5\%$) of primary quartz. Within a few inches of the contact with the greywacke the syenite is fine-grained (average grain size of equigranular feldspar 0 15 mm.) and in hand specimen has the colour, texture, and jointing of fine-grained greywacke. A thin section of a specimen from this marginal facies at the contact in Coal Creek shows that it has a similar mineralogical composition to the main mass of the syenite except that the ferromagnesian mineral is entirely alkaline amphibole ($Z \wedge c = 22°$, X = pale yellow, Y = yellow, Z = bluish-green, $\gamma - \alpha = 0{\cdot}012$). This section also showed occasional grains of titanite, strongly pleochroic (yellow to reddish-brown).

The mineralogical and chemical composition of the rock shows that the rock is a typical syenite in the broad sense of the term. It is distinctly alkaline, as shown by the presence of aegirine and alkaline amphibole, and is comparable with the umptekites and nordmarkites. Indeed, the rock is a nordmarkite as this term is defined by Barth (1945, p. 85) ". . . Nordmarkite [is] a syenite or quartz-syenite containing alkali feldspar (perthite or anorthoclase) without determinable amounts of plagioclase." It is very similar in composition to some of the type nordmarkites of the Oslo region.

The structural classification of this syenite intrusion is not clear-cut. It is transgressive to the general strike (about N.–S.) of the country rock. It is possibly a stock, although the noncommittal term pluton is perhaps preferable.

B. The gabbro

The presence of the gabbro was first inferred from the finding of pebbles of this rock in the gravels of the Mandamus and Dove Rivers.

When these were traced to the outcrop it was found that this rock has a very limited distribution. It crops out for about half a mile along Hut Creek, a tributary of the Dove River about two hours walking distance beyond the end of the road at Island Hills station. Along the banks of Hut Creek terrace gravels conceal the gabbro, and the surrounding hill slopes are of greywacke. Erosion has proceeded far enough to unroof the intrusion along the bed of the creek only. The creek is roughly at grade where it flows over the gabbro, but drops into a shallow gorge below the intrusion; the resistant nature of the gabbro compared to the country rock is evidently responsible for this.

On account of the limited exposure little can be said about the field and structural relations of the gabbro to the country rock. A normal intrusive contact is exposed in Hut Creek between the gabbro and a fine-grained greywacke. The greywacke is slightly reddened close to the igneous rock, but otherwise not noticeably altered. The gabbro is finer in grain for a few inches from the contact. The structural nature of the intrusion can hardly be deduced from the field relations, but it may be described as a stock. The general coarse grain of the gabbro suggests it is the product of the slow cooling of a considerable body of magma.

In hand specimen the gabbro has a distinctly porphyritic appearance, due to the presence of prominent crystals of augite, which may reach 10 mm. in greatest dimension, although the average is about 5 mm. The groundmass is plagioclase feldspar. Small flakes of biotite, occasional olivine crystals, and metallic grains of magnetite and ilmenite can be seen with a hand lens.

Under the microscope the rock is seen to consist essentially of augite and plagioclase (average composition about An_{45}) with minor amounts of biotite, olivine, and black opaque material (magnetite and ilmenite), and a small amount of apatite (see Table 2). Some brown hornblende was observed in a few specimens. A few grains of feldspar of low refractive index ($< 1{\cdot}540$), probably anorthoclase, were observed in a concentrate of light minerals from the analyzed gabbro. The proportion of augite to feldspar varies considerably from thin section to thin section, but this is probably due to the coarseness in grain of the rock. The rock is very fresh, olivine being the only mineral to show signs of alteration; occasionally it is partly or wholly changed to green serpentinous material. The augite is pale purplish-brown in colour, and somewhat pleochroic, suggesting a moderate titanium content; its optical properties are $\alpha = 1{\cdot}687$, $\beta = 1{\cdot}692$, $\gamma = 1{\cdot}715$, (+), $2V = 45°$, which from Hess's data (1949) indicates a composition of $Wo_{40}En_{42}Fs_{18}$. The olivine is optically negative, with an axial angle of 88°, corresponding to a composition of $Fo_{82}Fa_{18}$, considerably more magnesian than the augite, as would be expected if the olivine were the first to crystallize. The biotite generally mantles the ilmenite and magnetite and is strongly pleochroic from pale yellow to almost opaque, suggesting a high titanium content.

Over its limited exposure the gabbro appears to be fairly uniform, although it is occasionally somewhat finer in grain than the typical material described above. The only aberrant type was collected near the boundary against the greywacke at the upstream end of the gabbro. This rock is much lighter in colour than the normal gabbro and in hand specimen shows plagioclase laths averaging about 3–5 mm. in length; it is completely without augite phenocrysts. In thin section the rock is seen to consist for the most part of feldspar, with accessory magnetite, ilmenite and apatite. It is practically free from ferromagnesian minerals. Some secondary calcite is present. The outcrop of this rock is small and isolated, and its field relationship to the normal gabbro is not visible It is either a variant of the gabbro or a dyke cutting the gabbro.

Both mineralogical and chemical composition indicate that the rock of this intrusion, although gabbroic in appearance and general features, cannot be strictly classed with the gabbros, the average composition of the feldspar being andesine rather than labradorite. To call it a diorite would be misleading; in effect it is an andesine gabbro, if such a name were not to some extent self-contradictory. Its closest relative among named rocks is kauaiite, described by Cross (1915, p. 16) from the island of Kauai in the Hawaii group. The rock name kauaiite has recently been more precisely defined on a mineralogical basis by Barth (1945, p. 31) and applied to some rocks of the Oslo region originally classed as essexites. The Hut Creek gabbro shows a close relationship both in chemical and mineralogical composition with the original kauaiite from Kauai and the Oslo "essexites".

C. The hypabyssal rocks

The hypabyssal rocks of the area are mainly sills intruded along bedding planes in the greywackes and argillites. They are generally quite thin, the thickest measured being 16 feet; the average thickness is about four feet. They occur in an area surrounding the intrusions of syenite and gabbro and fall off rapidly in numbers on going outwards from these intrusions. The situation is complicated along the Pahau River by the presence of small intrusions for the full length of the river, far beyond the limits of this map. These are not dealt with in this paper, as they are probably not directly connected with the syenite and gabbro, and some are quite distinct, apparently being feeding channels through which Middle Tertiary basalts and agglomerates were extruded.

These hypabyssal intrusives are best exposed in the banks of the Dove and Mandamus rivers, and along the ridges in the area. They are particularly abundant along the Dove River, in Hut Creek, and in the vicinity of Charing Cross. Only those actually observed in place are recorded on the map, which is therefore not a true record of their abundance. Undoubtedly many are concealed by soil and vegetation, and some types were collected only as pebbles and as float.

The principal rock types are porphyries and porphyrites, although a variety of other types, mainly carrying porphyritic augite and/or olivine were collected. The porphyries are grouped around the syenite and are evidently directly connected with it (compare analyses of syenite and porphyritic trachyte), the porphyrites around the gabbro.

The sills associated with the syenite, which are well exposed in the lower course of the Dove River, are porphyritic trachytes very similar in chemical composition (Table 3) to the syenite itself. In hand specimen the rocks show feldspar phenocrysts up to 5 mm. long in a grey stony groundmass. The phenocrysts are of anorthoclase ($2V = 45°–50°$), the groundmass consists of the same feldspar in laths about 0·2–0·3 mm. long with a distinctly trachytic texture. In most of these trachytes feldspar makes up about 80% of the rock, and the remainder is entirely or almost entirely amphibole; in a few sills the amount of mafic minerals is very small and the rocks approach bostonites. When the amphibole is well-crystallized, as in the analyzed specimen, it is generally an alkaline type with blue-green to green-brown pleochroism, but it is often an exceedingly fine aggregate of brown colour, which can only tentatively be identified. In some of these trachytes a little opaque material (mostly pyrite) is present, and a little (± 1%) interstitial quartz was observed in most thin sections. Some secondary carbonates are generally present.

The plagioclase porphyrites are found in the eastern and northern parts of the area, around the gabbro intrusion, to which they are clearly related genetically. They are especially abundant and well exposed in the lower part of Hut Creek, below the gabbro, and in the adjacent part of the Dove River. Similar types are evidently abundant around Charing Cross and in the headwaters of the Awatui and Cascade streams, judging from the large amount of float in this part of the district, but solid rock is largely concealed by the mantle of waste. These plagioclase porphyrites are fairly uniform in appearance and composition; in hand specimen they show feldspar phenocrysts 4–5 mm. long in a grey or brownish-grey stony groundmass. Under the microscope the feldspar is found to be plagioclase (An_{45-50}): feldspar phenocrysts and groundmass make up 60–80% of most specimens, and the remainder is often a yellow-brown mesostasis, probably chlorite or amphibole. Some opaque material (magnetite, pyrite, and ilmenite) is generally present, and sometimes apatite. Most of these plagioclase porphyrites show considerable amounts (± 10%) of secondary carbonate.

The plagioclase porphyrites as described above are the commonest sills associated with the gabbro, but some sills contain augite phenocrysts in addition to those of plagioclase, and more rarely the plagioclase phenocrysts are entirely absent. A few grains of olivine, often altered, are found in the augite-rich types.

Of particular interest among the sills are the rare lamprophyric types which have only been found within or close to the syenite. Where the syenite is well exposed, in the gorge of the Mandamus River, it is seen to be cut in some places by numerous small intrusions, generally not more than about a foot thick. They are composed of dark, aphanitic rock and are lamprophyric in character, being comprised essentially of orthoclase, biotite, and blue-green amphibole, in uniform-sized crystals about 0·1–0 3 mm. long, the ferromagnesians exceeding the feldspar in amount. Rosiwal analysis of a typical specimen gave the following result (in weight %):

Orthoclase (possibly a little sodic plagioclase also)	33%
Amphibole and biotite (in approximately equal amounts)	64%
Calcite	1%
Opaque (mostly pyrite)	2%

a composition which may be described as a hornblende minette.

An interesting rock type was collected on the Hurunui Peak ridge about 60 chains east of the trig. station. The outcrop was a small isolated one and its geological relations could not be observed, but it appears to be a sill or dyke cutting the syenite. In hand specimen the rock is dense and black, with a few very small crystals visible to the naked eye; its fracture is almost glassy. Thin sections show phenocrysts of sanidine, sodalite, brown hornblende, aegirine, and magnetite in an almost opaque groundmass; under high magnification the groundmass is seen to consist of colourless material thickly peppered with small dark equant crystals which are probably a ferromagnesian mineral. At first glance the colourless groundmass appears isotropic, but in parts it shows vague birefringence suggesting beginning crystallization of feldspar; it is probably a devitrified glass. Table 4 gives an analysis of this rock; it is interesting for the high content of nepheline shown in the norm, the highest that has been recorded for rocks from this area. Some of the nepheline in the norm is represented by sodalite phenocrysts, but a considerable proportion is occult in the groundmass. It is difficult to find a satisfactory name for the rock, but sodalite phonolite fits it best. This rock is similar in chemical composition (except for H_2O+) to heronite, an analcitic dyke rock from Heron Bay, Lake Superior (Coleman, 1899).

D. The igneous breccia

The igneous breccia occurs in association with the syenite and is not differentiated from it on the map, mainly because it covers a comparatively small area around Hurunui Peak, and the actual contact with the associated syenite was nowhere seen. It forms the crest of Hurunui Peak itself and is found on the spurs leading down from this point. It makes prominent outcrops, but its field relationship to the syenite is obscured by the mantle of waste. It appears to be a capping over the syenite intrusion and is interpreted as having been formed by the shattering of the roof of the magma chamber by gas pressure in the last stages of crystallization of the syenite.

This igneous breccia is a mass of angular fragments in a fine-grained groundmass. These fragments range in greatest dimension from a foot down to a fraction of an inch, and consist mainly of syenite and trachyte with subordinate greywacke and argillite. The groundmass weathers more rapidly than the fragments, so that they stand out in relief on weathered surfaces (Fig. 3).

Under the microscope the groundmass is seen to be almost entirely feldspar laths, generally very small (up to 0·01 mm. long) with minute grains (< 0.005 mm.) of what appear to be an alkaline amphibole peppered throughout. Flow structure is generally marked in the groundmass. Sometimes the breccia carries numerous equidimensional feldspar crystals about 1 mm. long.

Table 5 gives an analysis of material from the summit of Hurunui Peak (chosen to determine the composition of the groundmass and hence as free of fragments as possible), and shows that its composition is very close to that of the syenite and trachyte. The same magma from which the syenite and trachyte were formed evidently gave rise to the igneous breccia. The analysis shows somewhat higher alumina than the analyses of the syenite and the trachyte. This gives rise to the 3 75% corundum in the norm, and may be due to the presence of some argillite fragments in the analysed sample.

The presence of this igneous breccia is of particular significance for deciphering the conditions under which the syenite itself crystallized. The composition of the syenite and the composition of the groundmass of the igneous breccia correspond so closely that they must have formed from the same magma. The presence of the igneous breccia is believed to indicate that the syenite crystallized under a comparatively thin and weak roof. As the syenite crystallized the remaining magmatic liquid became more highly charged with volatiles (chiefly water) until the pressure was sufficient to cause an explosive shattering of the roof (partly greywacke and argillite and partly previously solidified syenite). The rapid expulsion of the remaining magma into this shattered mass cemented it together into this igneous breccia, at the same time giving rise to the remarkable porosity and friability of the syenite.

NATURE AND ORIGIN OF THE ROCKS

The chemical affinities of the rocks are perhaps most simply and clearly expressed by the alkali-lime index, as introduced by Peacock (1931). By plotting the analyses of the igneous rocks of this area the alkali-lime index is found to be 52 5, which would place these rocks in Peacock's alkali-calcic group, not far from the boundary with alkalic group, which is at an alkali-lime index of 51. This correlates well with the mineralogy of the rocks themselves. In general terms the alkalic group and the alkali-calcic group are distinguished mineralogically by the occurrence of feldspathoids in the former and their absence in the latter. The Mandamus-Pahau intrusive rocks are free from feldspathoids (except for the sodalite phonolite, which probably represents an extreme differentiate) but are distinctly alkaline in character, as evidenced by the biotite and the small amount of anorthoclase in the gabbro, and the alkaline pyroxenes and amphiboles in the syenite and trachytes.

The relationship of the Mandamus-Pahau intrusives—geological, mineralogical, and chemical—suggests that they have differentiated from a common parent magma. The visible amount of the syenite is very much greater than that of the gabbro (it is of course dangerous to draw conclusions regarding the absolute amounts of the different intrusives on the basis of surface exposure). With these circumstances in mind, the writer suggests that the parent magma of the intrusive rocks of the Mandamus-Pahau area was intermediate in composition between the syenite and the gabbro, and that the gabbro represents an accumulation of early-formed crystals from this magma. This accumulation of early-formed crystals was separated from the remaining liquid by pressure due to crustal movements, and this liquid was injected into higher levels in the crust and formed the syenites and trachytes.

This concept of the origin of the syenite and trachytes as the products of crystallization of a magmatic liquid from which the products of early crystallization had been removed is supported by certain criteria developed by Bowen (1937). He points out that the laboratory study of silicate systems indicates that the residual liquids from the fractional crystallization of complex silicate magmas must be enriched in alkali-alumina silicate; the alkali-alumina silicate system ($NaAlSiO_4$–$KAlSiO_4$–SiO_2) may thus be referred to as petrogeny's "residual" system. The laboratory study of this system has shown that it has a well-defined valley in the fusion surface, which is, of course, the composition area of the liquids having the lowest temperature of crystallization in the system. Bowen showed that the composition of many igneous rocks rich in alkali-alumina silicates, when plotted in terms of the $NaAlSiO_4$–$KAlSiO_4$–SiO_2 system, fell within this valley in the fusion surface, thus indicating that crystal $\rightleftarrows$ liquid equilibrium had been the dominant control in the production of these rocks, i.e. they represented the residual liquids of crystallizing magmas. Benson (1941) applied Bowen's criteria to the salic rock types of the Tertiary igneous rocks of the North Island, Banks Peninsula, and the Dunedin district, and showed that the idea that these rocks represented the solidification products of residual magmatic liquids was thereby supported. Bowen's scheme of plotting has been applied to the Mandamus syenite, trachyte, and phonolite, and the result is shown in Fig. 4. This figure shows that the composition of the alkali-alumina silicate in these rocks falls in the low-melting region of the diagram; for the syenite and the trachyte the points fall near the minimum between albite and orthoclase, and the point for the phonolite practically coincides with the lowest temperature in the diagram. This strongly supports the belief that these rocks represent late fractions of a magma whose evolution has largely been that of differentiation by fractional crystallization.

Comparison with Other Areas

The intrusive rocks of the Mandamus-Pahau area show a marked resemblance to some of the classic types of the Oslo region. The syenite can be matched chemically and mineralogically with the nordmarkites of the Oslo region, and the gabbro is strictly comparable with the well-known Oslo essexites which Barth (1944, pp. 26–31) has shown not to be essexites at all, since they contain no nepheline; they are alkaline gabbros which may be classified as kauaiites, the original kauaiite being described from Kauai, in the Hawaiian Islands (Iddings, 1913, p. 173; Cross, 1915, p. 16). The Mandamus-Pahau intrusives are, of course, small in comparison to those of the Oslo region and are very much less diversified, but in both regions the major types are similar, suggesting parent magmas of comparable composition.

Within New Zealand the Mandamus-Pahau rocks show chemical and mineralogical resemblances to those of the Dunedin district, although the rocks of the latter district are mainly extrusives. The rocks of the Dunedin district are somewhat alkaline (alkali-lime index 50·1), which is reflected in the presence of numerous feldspathoidal types which are absent in the Mandamus-Pahau area. However, if the feldspathoidal types are omitted, the alkali-lime index for the rocks of the Dunedin district is then practically identical with that for the Mandamus-Pahau rocks. The similarities are particularly marked in the trachytes which are common to both areas. The trachytes described by Marshall (1906, 1914) from North Head and Portobello are mineralogically and chemically comparable with those of the Mandamus-Pahau area.

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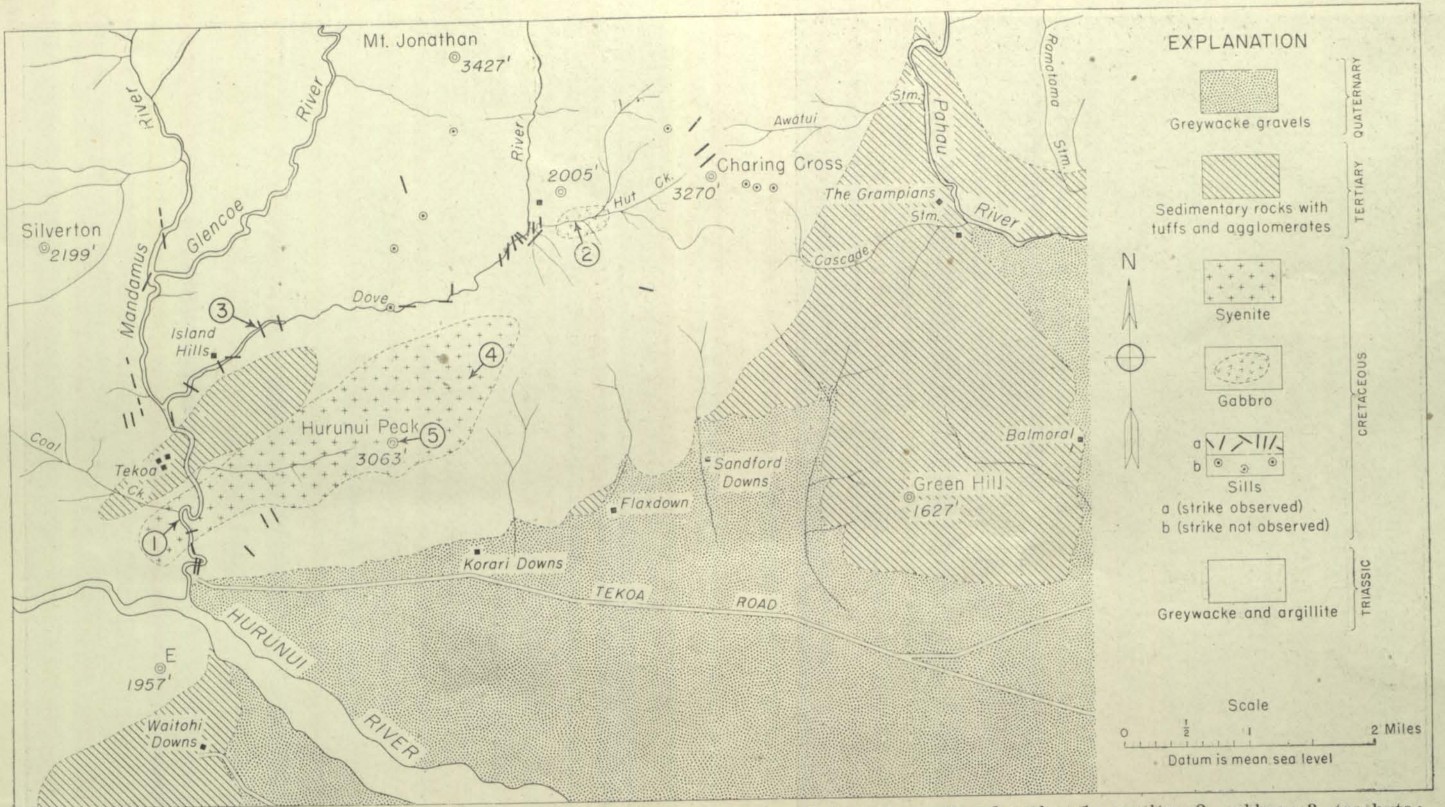

FIG. 1—Geological map of the Mandamus-Pahau area; the figures give the location of the analysed rocks: 1, syenite; 2, gabbro; 3, trachyte; 4, phonolite; 5, igneous breccia. (The Tekoa Road ends at Island Hills Station, although it is not shown beyond the Mandamus River, in order to avoid crowding the map.)

FIG. 2—Hand specimen of analysed syenite (length of specimen is three inches).

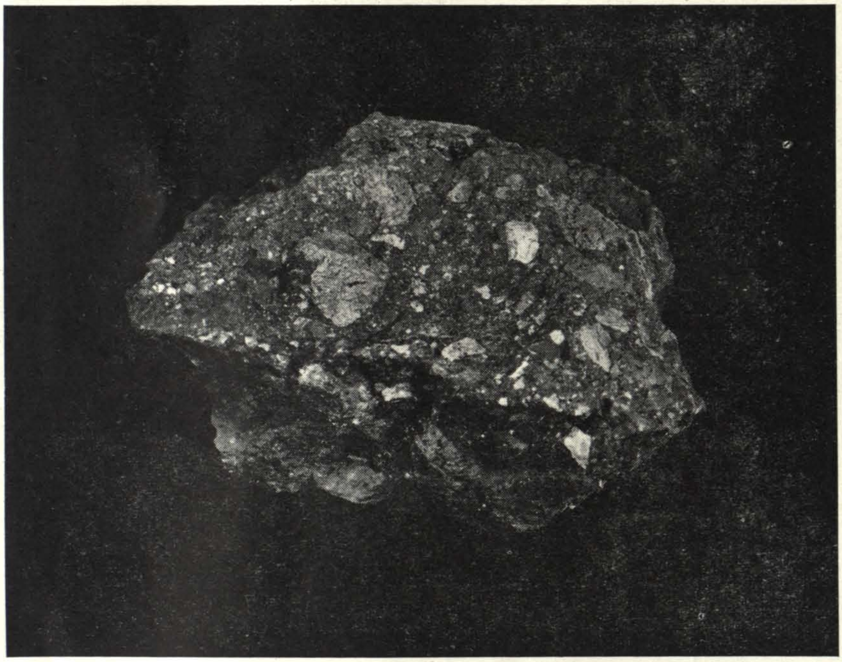

FIG. 3—Hand specimen of igneous breccia (length of specimen is five inches).

Rocks related both in geological occurrence and in chemical and mineralogical composition probably occur in the mountains to the south of the Mandamus-Pahau area, around the headwaters of the Waipara River. Benson (1942, pp. 177–8) has briefly described pebbles of doleritic and teschenitic types collected from the gravels of the Waipara River. They resemble the gabbro of the Mandamus-Pahau area in the presence of biotite and of minor amounts of alkali feldspar. Syenitic and trachytic types have not been observed.

Thomson (1912, 1919) described briefly some intrusive rock types from the Inland Kaikoura mountains. The rocks he described were mainly dolerites with alkaline affinities, similar to the gabbro described in this paper. A visit to this area in 1946 showed that the intrusive rocks cover a large area, extending from the headwaters of the Swale to those of the Muzzle River, and are considerably diversified in type. The syenite and gabbro from the Mandamus area are petrographically similar to some of the rocks from the Inland Kaikouras. Too much should not be made of this similarity, however, since the igneous rocks of the Inland Kaikouras have yet to be studied in detail and their mutual relations deciphered.

The closest analogies with the Mandamus-Pahau rocks are afforded by the small area of intrusive rocks at Onawe, in Akaroa harbour. These rocks, which were described in detail by Speight (1923, 1940), consist of gabbro and syenite, and some of the trachyte dykes of the Akaroa area are probably co-magmatic. The alkali-lime index of the Onawe rocks is 50·5, indicating that they are slightly more alkaline in general character. However, thin sections of the Onawe syenite and gabbro are very similar to sections of the syenite and gabbro from the Mandamus-Pahau area.

Much of the resemblance between the Mandamus syenites and trachytes and similar rocks at Onawe and in the Dunedin district may be due to their being all "residual magmas" in Bowen's sense, i.e. a final differentiate from the fractional crystallization of a large *body of magma. The marked resemblances, however, suggest that the original magma in all those localities was similar, and that the same* processes of differentiation were active in each case.

THE AGE AND CORRELATIONS OF THE INTRUSIONS

The intrusion of these rocks was probably associated in time with the Hokonui orogeny. They are injected into greywackes and argillites whose age has not been directly established by fossil evidence, but which are correlated on lithological and structural similarities with fossiliferous rocks of Triassic and Jurassic age in other parts of Canterbury (Mason, 1949). Pebbles of syenite and trachyte occur in the basal Tertiary conglomerates (Mangaorapan, i.e. Lower Eocene) in Coal Creek. On this evidence intrusion was post-Jurassic and pre-Eocene. It appears most probable that the intrusion accompanied or followed closely the orogenic movements that brought to a close the long period of Hokonui sedimentation. The fact that the syenite often shows strong jointing like that of the surrounding greywacke suggests that it has been subjected to similar forces, and that hence it was intruded before the orogenic movements were completely spent.

From this discussion the time of intrusion would be correlated with the Hokonui orogeny, and would thus be Lower Cretaceous. An alternate hypothesis, which would be difficult to prove but which cannot be ruled out on the available evidence, is that intrusion took place at the end of the Cretaceous period. A widespread break in the sedimentary sequence occurred in North Canterbury at the end of the Cretaceous. Over a considerable area, post-Hokonui sedimentation begins with Mangaorapan beds. This stratigraphic break, though not at all comparable with that due to the Hokonui orogeny, is nevertheless an important one, and it must be borne in mind when attempting to date this igneous activity.

As mentioned in the introduction, igneous rocks associated with the Hokonui orogeny are rare. The large areas of Triassic and Jurassic rocks, both in North and South Islands, are monotonously free of associated igneous rocks. Probably the most extensive occurrence of intrusions in these rocks is that of the Inland Kaikoura mountains, which has yet to be mapped and examined in detail. Thomson considered that the igneous rocks of the Inland Kaikoura mountains were intruded in Clarentian (Lower Cretaceous) times. If this dating is correct, and the Mandamus-Pahau rocks are the same age, this implies that the Mandamus-Pahau rocks were intruded after the end of the Hokonui orogeny, rather than during the later stages of the orogeny itself.

Unfortunately, little evidence is available for dating the Onawe syenite and gabbro, which show such marked resemblances to the Mandamus-Pahau rocks. What evidence there is, however, does not conflict with the postulate that the intrusives in both areas may be of the same age. Speight's opinion (1940) was that the Onawe rocks are part of an older and distinct substratum belonging to an earlier epoch than that of the main mass of the Akaroa volcano; however, he made no statement as to their probable age.

General History of the Intrusion

It is believed that the rocks described in this paper were all derived from a common magmatic source by a process of differentiation by crystallization. The nature of the source magma is a matter of conjecture, but it was presumably such that both the gabbro and the syenite rocks were derived from it, the gabbro representing an accumulation of the early formed crystals and the syenite the crystallization product of the remaining magmatic liquid. This concept of the syenitic rocks as being the products of crystallization of a residual magmatic liquid is supported by the way in which the composition of the salic material in the actual rocks when plotted on the $NaAlSiO_4$–$KAlSiO_4$–SiO_2 diagram of Bowen (1937) falls in the low-melting "residual liquid" section (Figure 4). The points representing the rocks from this district occupy an area on Bowen's diagram corresponding to that set out by Benson (1941, p. 542) for the salic portion of the residual magmas of the Dunedin petrographic province.

In view of the absence of rocks intermediate between those of gabbroic and syenitic composition it is believed that the residual liquid from which the syenitic rocks were formed was isolated by crustal stresses from the early formed crystals of augite and plagioclase which

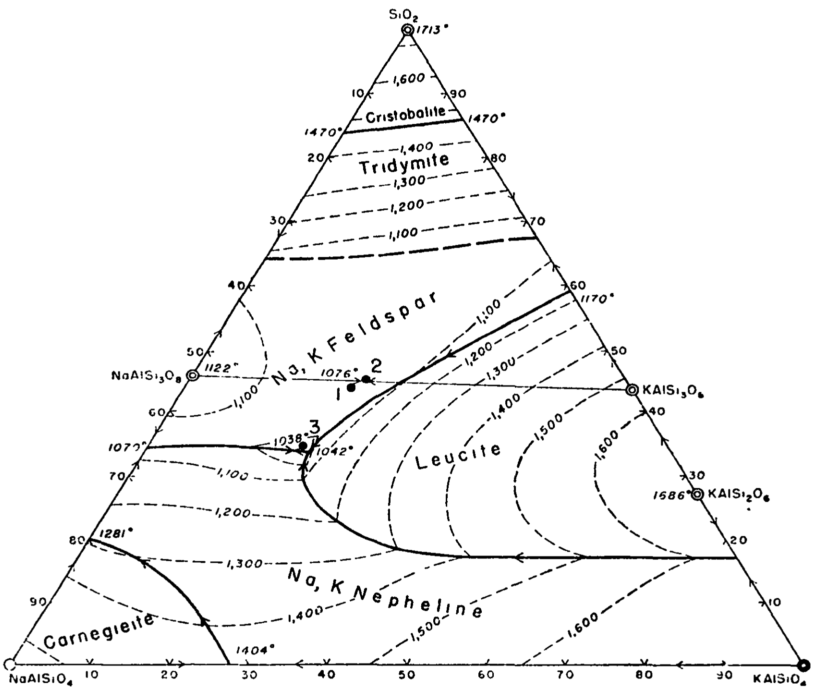

FIG. 4—Compositions (less anorthite) of the salic portions of syenite (1), trachyte (2), and phonolite (3), from the Mandamus-Pahau area.

now constitute the gabbro. This "squeezed-out" residual magma then crystallized itself as microperthite, with some ferromagnesian material. As this residual magma cooled and crystallization proceeded the concentration of volatiles, particularly water vapour, in the still liquid fraction increased greatly. During this period part of the magma was injected along bedding planes in the country rock to form the numerous trachytic sills extending out from the intrusion. When the greater part, perhaps 80–90%, of the residual magma had crystallized, and the magma chamber contained a mush of crystals of microperthite and ferromagnesian minerals with liquid in the interstices, the pressure of volatiles was sufficient to shatter the relatively thin roof of the intrusion. This explosive release of pressure drove most of the remaining liquid out of the mush of crystals into the fragmented roof, where it solidified as the matrix of the igneous breccia. The forcible expulsion of the residual fluid from the interstices of the syenite gave it the remarkably porous and friable character.

TABLE 1. ANALYSIS OF SYENITE, JUNCTION OF COAL CREEK AND MANDAMUS RIVER
Analyst: T. A. Rafter

	Weight %	Mol. Prop. × 100	Norm		Mode (Weight %)	
SiO_2	61.23	101.95	or	32.00	Microperthite	85
CO_2	0.32	0.73	ab	52.90	Ferromagnesian[1]	8.3
TiO_2	0.64	0.80	ne	1.76	Natrolite and calcite	3.9
ZrO_2	nt. fd.		Σ sal	86.66		
Al_2O_3	16.78	16.46			Opaque	2.8
Fe_2O_3	2.84	1.78	ac	2.40		
Cr_2O_3	nt fd.		di	3.68		100.0
FeO	2.84	3.95	ol	1.05		
MnO	0.19	0 27	mt	2.92		
MgO	0.18	0.45	il	1.21		
CaO	1.26	2.25	Σ fem	11.26		
BaO	nt fd.		cc	0.73		
Na_2O	6.96	11.23				
K_2O	5.42	5.75				
P_2O_5	nt. fd.					
S	0.05					
H_2O+	0.96					
H_2O-	0.24					
Cl	trace					
	99.91	C.I.P.W. System. I. 5 1 4.—Nordmarkose Shand System: XSkLβ—Peralkaline Syenite Density: 2 62 (low, because of porosity of rock)				

[1] Subequal amounts of aegirine, biotite, and alkaline amphibole.

TABLE 2. ANALYSIS OF OLIVINE GABBRO, HUT CREEK
Analyst: T. A. Rafter

	Weight %	Mol. Prop. × 100	Norm		Mode[1] (Weight %)	
SiO_2	47.78	79.55	or	6.73	Plagioclase[2] (average An_{45})	51
CO_2	0.37	0.84	ab	25.22		
TiO_2	3 22	4.03	an	15.82	Augite	33
ZrO_2	nt fd.		ne	0.54	Olivine	6.0
					Biotite	2.3
Al_2O_3	12.13	11.90	Σ sal	48.31	Apatite	1.0
Fe_2O_3	2.38	1.49			Opaque	6.7
Cr_2O_3	0.08		di	26.25		
FeO	8 27	11.51	ol	12.74		100.0
MnO	0.19	0.27	mt	3.22		
MgO	8.79	21 80	il	6.12		
CaO	10 93	19.49	ap	1.25		
BaO	0.02		pr	0.25		
Na_2O	3 10	5.00	Σ fem	49.83		
K_2O	1 14	1 21	cc	0.84		
P_2O_5	0.53	0 37				
S	0.13	0.41				
H_2O+	1.17					
H_2O-	0.25					
Cl	trace					
	100 48	C.I.P.W. System: III. 5. 3. 4.—Camptonose. Shand System XVmM'γ—Metaluminous Sub-Gabbro Density = 3 04 (analysed specimen; other samples, richer in mafic minerals, gave values up to 3.27).				
—O = S	0.05					
	100.43					

[2] Includes a small amount of interstitial anorthoclase.

[1] Rosiwal analyses of different thin sections of gabbro show the following range in mineral composition Plagioclase 26–53%, augite 30–60%, olivine 4–10%, biotite 2–9% ores 4-8% the figures given represent an average for a number of sections

TABLE 3. ANALYSIS OF TRACHYTE, SILL IN BED OF DOVE RIVER, 110 CHAINS AT 312° FROM HURUNUI PEAK

Analyst: T. A. Rafter

	Weight %	Mol. Prop. × 100	Norm		Mode (Weight %)	
SiO_2	60.38	100.53	Q	0.31	Anorthoclase	73
ZrO_2	0.15	0.12	Z	0.22	Alkaline amphibole	22
CO_2	1.50	3.41	or	31.05	Quartz	1.2
TiO_2	0.59	0.74	ab	48.55	Calcite	3.3
					Pyrite	0.5
Al_2O_3	15.13	14.84	Σ sal	80.13		
Fe_2O_3	2.19	1.37				100.0
Cr_2O_3	nt. fd.		ac	3.88		
Rare			di	2.59		
Earths	0.05		hy	6.76		
FeO	4.23	5.89	mt	0.46		
MnO	0.25	0.35	il	1.12		
			pr	0.80		
MgO	0.45	1.12				
CaO	2.51	4.48	Σ fem	15.61		
BaO	0.02					
Na_2O	6.26	10.10	cc	3.41		
K_2O	5.26	5.58				
P_2O_5	0.01					
S	0.43	1.34				
H_2O+	0.68					
H_2O-	0.22					
Cl	trace					
	100.31	C.I.P.W. System: II. 5. 1. 4.—Umptekose.				
−O = S	0.15	Shand System DSkLβ—Peralkaline Trachyte.				
	100.16	Density = 2.67.				

TABLE 4 ANALYSIS OF SODALITE PHONOLITE, TOP OF RIDGE, 60 CHAINS AT 51° FROM HURUNUI PEAK

Analyst: M. C. Coller

	Weight %	Mol. Prop. × 100	Norm		Mode (Volume %)	
SiO_2	52.45	87.33	or	25.93	Goundmass	90
TiO_2	1.20	1.50	ab	30.25	Sanidine	4.3
Al_2O_3	20.57	20.18	an	10.54	Sodalite	2.8
Fe_2O_3	2.31	1.45	ne	16.93	Aegirine-augite	0.8
FeO	3.59	5.00	hl	1.85	Brown hornblende	2.1
MnO	0.24	0.34	Σ sal	85.50		100.0
MgO	1.32	3.27				
CaO	3.33	5.94	di	3.71		
Na_2O	7.76	12.52	ol	3.40		
K_2O	4.39	4.66	mt	3.26		
Cl	0.56	1.58	ap	0.54		
P_2O_5	0.22	0.16	il	2.28		
H_2O+	1.39	7.72	Σ fem	13.19		
H_2O-	0.13					
	99.46	C.I.P.W. System: II. 6. 2. 4.—Essexose.				
−O = Cl	0.12	Shand System: DUmLβ—Metaluminous Phonolite.				
	99.34	Density = 2.66				

TABLE 5. ANALYSIS OF TRACHYTIC MATRIX OF IGNEOUS BRECCIA, SUMMIT OF HURUNUI PEAK
Analyst: T. A. Rafter

	Weight %	Mol. Prop. × 100	Norm		Mode (Calculated)	
SiO_2	59.99	99.88	Q	1.73	Anorthoclase	89
ZrO_2	0.10	0.08	Z	0.14	Quartz	2
CO_2	0.06	0.14	C	3.75	Ferromagnesian }	9
TiO_2	0.63	0 79	or	32.61	Opaque }	
Al_2O_3	20 06	19.68	ab	50.91		——
Fe_2O_3	2.13	1.33	an	1.20		100
Cr_2O_3	trace		Σ sal	90.34		
Rare Earths	0 03					
FeO	2 29	3.19	hy	3.05		
MnO	0.12	0.17	mt	3.08		
MgO	0.56	1.39	il	1.21		
CaO	0.39	0.70	ap	0.14		
BaO	0.08		Σ fem	7.48		
Na_2O	6.02	9.71				
K_2O	5 52	5.86	cc	0.14		
P_2O_5	0.06	0 04				
S	0.01					
H_2O+	1.43					
H_2O-	0 38					
Cl	trace					
	99.86	C.I.P.W. System: I. 5. 1. 3.—Phlegrose. Shand System: DSpLβ—Peraluminous Trachyte. Density = 2.66.				

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