# Mineralogical Notes from the University of Otago, New Zealand—No. 2.

## COMPARATIVE COMPOSITION-VARIATION DIAGRAMS FOR THE CAINOZOIC IGNEOUS ROCKS OF NEW ZEALAND WITH DETERMINATIONS OF THE OPTIC AXIAL ANGLES OF THE PYROXENES AND OLIVINES CONTAINED THEREIN.

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### MATERIAL STUDIED.

ATTENTION has lately been given to the composition of pyroxenes in basic lavas in the Pacific region and in other parts of the world, and its significance in petrogenesis has been much discussed (e.g., by Barth 1931, Tsuboi 1932, Kennedy 1933, and Kuno 1936). To test the extent to which the generalisations that have been advanced may be applied to the Cainozoic lavas of New Zealand, the optic axial angles of pyroxenes and olivines have been measured in the case of thirty-nine representative rocks from three regions.

In order to indicate quantitatively the general character of the petrographic association in each of these regions, two variation diagrams are given which have been based on the available good analyses of New Zealand Cainozoic lavas, nearly two hundred in all, of which the greater proportion are the work of F. T. Seelye, while of the remainder, including most of those from the Dunedin District, the majority are the work of Dr. P. Marshall. Of the two diagrams, Fig. 1 shows the conventional smoothed-curve variation diagram of the principal oxides in A the lavas in the North Island, B the lavas of Banks' Peninsula, D the lavas of the Dunedin district free from essential amounts of modal feldspathoids and/or alkaline pyroxene, and D.al Dunedin lavas of a more alkaline character. Figures 2 and 3 show the actual distribution of points in the plotting of the analyses used in obtaining the smoothed variation curves for calc-alkaline and alkaline igneous rocks of the Dunedin district. Figure 4 illustrates the variation of the norm-compositions calculated from the analyses utilised in preparing the curves A, B, and D in Figure 1. Separate curves are given for the lavas of the North Auckland Peninsula and the vicinity of Auckland City (A1), for the south-east of the Auckland Province (Cape Colville Peninsula and the Rotorua-Taupo region) (A2), and for the south-west of the Auckland Province and Taranaki (A3). Figure 5 illustrates for the Late Cainozoic rocks of Banks' Peninsula the distribution of points in the plotting of the norm-compositions on which the smoothed variation curves were drawn. (The Akaroa syenite probably does not belong to this rock-series.)

Broadly characterised the first of these areas (see *N.Z. Geological Survey Bulletins,* Nos. 8, 27, 34) possesses a basement of highly folded Mesozoic greywacke and argillite partially covered by

Cretaceous and Tertiary sandstones, mudstones, and occasionally limestones. The effusive rocks are Mid-Tertiary rhyolites, dacites and pyroxene-andesites, Lower Pliocene olivine-andesite, dacite and rhyolites, and widespread Late Pliocene to Recent basalts. The latter alone occur in the Auckland urban area, and have slightly alkaline features as shown by the occasional presence of *normative* (not modal) nepheline, and a small mass of pegmatoid nephelinite ("luscladite") in a single locality. The only rocks from the North Island in which the optic axial angles have been determined by the writers are from this basaltic group. In the South-eastern portion of the Auckland Province (see *N.Z. Geological Survey Bulletins*, Nos. 4, 15, 16, 26, 37) the cover of Cretaceous sediments above the folded Mesozoic greywackes is lacking, and that of the Tertiary sediments is relatively thin or absent. In the Cape Colville Peninsula the sequence of volcanic eruptions is broadly Miocene andesites, dacites and rhyolites, Late Miocene andesites, quartz-andesites and dacites, and Pliocene to Early Pleistocene rhyolites, each division containing fragmental as well as massive ejectamenta. In the Rotorua-Taupo region the record is more varied, Miocene andesite being followed by Pliocene andesite, dacite and subordinate basalts, while Pleistocene rhyolite and very subordinate basaltic eruptions also have continued into Recent times. In South-west Auckland and Taranaki (see *N.Z. Geological Survey Bulletins*, Nos. 14, 14, 28, 29) there is commonly, though not always, a very thick cover of Tertiary marine sediments above the Mesozoic greywackes. A small amount of Miocene andesite and tuff occurs, but in the North are Late Pliocene to Recent olivine-andesites and weakly alkaline olivine-basalts, and in the South-west varied Late Pliocene to Pleistocene andesites. Optic axial angles of the pyroxenes in the various andesites and dacites of the above regions have not yet been measured, and it is hoped to extend these studies to deal with them as opportunity offers.

On Banks' Peninsula the basement rocks are also folded Mesozoic greywackes, upon the eroded surface of which rest basalts and andesites of probably Late Mesozoic age followed in turn by a little Mid-Tertiary sandstone and still younger rhyolites and pitchstones. The Late Cainozoic basalts and andesites that make up the bulk of Banks' Peninsula (see Speight, 1917, 1922, 1923, 1924, 1926, 1936, 1938) lie upon the eroded surface of these rocks. The basalt is on the average rather more alkaline than that of the North Island, and occasionally the analyses indicate a little normative nepheline though the mineral is never seen modally. The volcanic series ranges up through basalt and dolerite to olivine-andesite, and is cut by trachytic dykes, some of which contain alkaline amphibole and approach phonolite in composition. Except in the case of trachytes containing possibly deuteric tridymite, none of the Late Cainozoic igneous rocks contains free silica.

The volcanic rocks of the Dunedin district rise through quartz-albite-chlorite-sericite-epidote-schists (derivatives of greywackes and argillites), and through part or all of the superimposed Cretaceous to Mid-Tertiary sandstones and mudstones, which are more or less calcareous in the upper portions. The range of rock-types is wider than in the other districts, for not only are there dolerites, basalts, trachybasalts, trachyandesites and trachytes free from distinctly alkaline minerals (see Fig. 2 for norm-variation) but also, in repeated association with the above, a more variable and distinctly alkaline series of ankaramites, kulaites, basanites, tinguaites, phonolites, etc., including hybrid and transitional rock-types, the compositions of which are too widely diverse to be indicated by any one series of curves (cf. Benson, 1934) such as those in Fig. 4.

The average composition of the Dunedin basalt is close to that of Banks' Peninsula, the chief differences being in the relative abundance of iron and magnesia. The average North Island basalt is clearly less alkaline, less titaniferous, and more calcic than that of Banks' Peninsula. This appears from the following table in which the second column of figures for Banks' Peninsula basalt includes five rocks classed as olivine-andesites. The averages may be compared with those for the olivine-labradorite-basalts of Victoria (Edwards 1938) and for those of the Pacific (Tyrrell 1937).

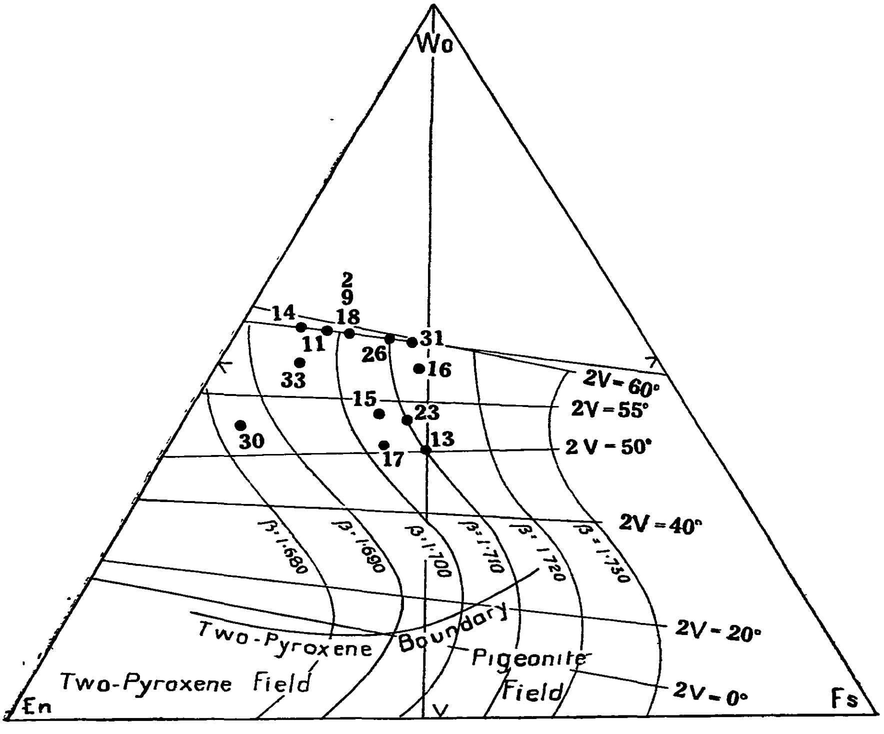
| | Dunedin. | Banks' Peninsula. | | N. Island. | Victoria. | Pacific. |
|---|---|---|---|---|---|---|
| Analyses. | 19 | 14 | 19 | 19 | 20 | 17 |
| $SiO_2$ .. | 48.18 | 49.14 | 49.17 | 49.33 | 49.78 | 47.6 |
| $Al_2O_3$ .. | 16.10 | 15.71 | 16.10 | 15.64 | 14.60 | 14.5 |
| $Fe_2O_3$ .. | 6.02 | 3.64 | 3.79 | 5.47 | 4.09 | 3.6 |
| FeO .. | 8.71 | 8.17 | 7.90 | 6.47 | 7.55 | 8.2 |
| MgO .. | 3.90 | 6.03 | 5.62 | 7.75 | 8.77 | 7.0 |
| CaO .. | 9.89 | 8.38 | 8.40 | 10.22 | 8.65 | 10.0 |
| $Na_2O$ .. | 3.49 | 3.69 | 3.74 | 3.14 | 2.85 | 3.0 |
| $K_2O$ .. | 1.56 | 1.39 | 1.46 | 0.98 | 1.29 | 1.1 |
| $TiO_2$ .. | 2.31 | 3.17 | 2.95 | 0.90 | 1.85 | 3.2 |
| $P_2O_5$ .. | 0.36 | 0.73 | 0.73 | 0.40 | 0.43 | 0.4 |
| MnO .. | — | 0.15 | 0.15 | 0.16 | 0.19 | 0.2 |

The normative mineral compositions calculated from these are as follows:—

| | Dunedin. | | Banks' Peninsula. | | | | N. Island. | | Victoria. | | Pacific. | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Mol | | Mol.. | | Mol. | | Mol. | | Mol. | | Mol |
| Feldspar. | | | | | | | | | | | | |
| Or .. | 8.90 | 10 | 8.34 | 10 | 8 90 | 10 | 6 12 | 7 | 7.78 | 10 | 6.7 | 8 |
| Ab .. | 28.8 | 35 | 30.92 | 38 | 31.44 | 38 | 26.72 | 35 | 24.10 | 32 | 27.2 | 37 |
| An .. | 23 91 | 55 | 21.96 | 52 | 22 80 | 52 | 25.30 | 58 | 23.07 | 58 | 21.7 | 55 |
| Ne .. | | % | 0 28 | % | ... | % | | % | .. | % | ... | % |
| | 61 63 | | 61.50 | | 63 14 | | 58.14 | | 54.95 | | 55.6 | |
| Pyroxene. | | | | | | | | | | | | |
| Wo .. | 9.51 | 50 | 6 50 | 50 | 6.15 | 36 | 9.51 | 37 | 7.31 | 23 | 10.7 | 45 |
| En .. | 5.20 | 32 | 4.20 | 37 | 7 10 | 46 | 12.20 | 53 | 16.20 | 62 | 8.8 | 42 |
| Fs .. | 3.96 | 18 | 1.85 | 13 | 3.56 | 18 | 2.90 | 10 | 5.68 | 15 | 3.6 | 13 |
| | 18 67 | . | 12.55 | | 16.81 | | 24.61 | | 29.19 | | 23.1 | |
| Olivine. | | | | | | | | | | | | |
| Fo .. | 3.15 | 64 | 7.63 | 74 | 4.90 | 73 | 5.04 | 84 | 4.06 | 78 | 6.0 | 75 |
| Fa .. | 2.45 | 36 | 3.78 | 26 | 2.65 | 27 | 1.22 | 16 | 1.63 | 22 | 2.9 | 25 |
| | 5 60 | | 11.41 | | 7.55 | | 6 26 | | 5.69 | | 8.9 | |
| Mt .. | 8.82 | | 5.34 | | 5.57 | | 7.89 | | 6.03 | | 5 3 | |
| Il .. | 4.41 | | 6.08 | | 5.46 | | 3.65 | | 3.50 | | 6.1 | |
| Ap .. | 10.1 | | 1.68 | | 1 68 | | 0.67 | | 1.01 | | 1.0 | |

From these figures it would appear that the average normative pyroxene in the basalts proper of Dunedin and Banks' Peninsula is mostly diopsidic, while that of the less alkaline North Island basalts often approaches more nearly to pigeonite as Kennedy's (1933) discussion would suggest. It further appears that the average normative olivine is richest in iron in the basalts of Dunedin and poorest therein in those of the North Island. Comparing the individual norms of analysed basalts, the tendency for increase in the proportion of fayalite in the normative olivine with increasing silica, though not clearly marked, is suggested in the Dunedin analyses, and to a less extent in those from Banks' Peninsula, but is not at all evident among the basalts of the North Island. (See Fig. 4.) As will be seen, the optical measurements recorded below indicate compositions of pyroxenes and olivine departing considerably from those calculated normatively, and vary greatly among themselves. The presence of alumina and titanium in the pyroxenes and the effects of crystal-sorting probably contribute to this.

A preliminary investigation of the optic axial angles of the phenocrystic pyroxenes in the Dunedin basalts was made by one of us (W.N.B.) utilising the graphic method described by Becke (1895, 1904). About sixty angles were measured. They ranged chiefly between 44° and 58°, with a few lower (lowest 38°) and a few reaching as high as 60°. It was not possible by the method employed to determine the optic axial angles of the individual layers in zoned



P–Q Two-Pyroxene Boundary.

Normative composition of pyroxenes in New Zealand basalts plotted on Kuno's (1936) diagram of the optic properties of monoclinic pyroxenes.

crystals or of the small groundmass pyroxenes or of the olivines. Subsequently a Leitz universal stage was obtained (with hemispheres of refractive index 1·554), and 220 measurements of optic axial angles were made by F. J. Turner, using the standard method as described by Nikitin (1936, pp. 32–38). The above total does not include those angles the measurement of which involved high angles of tilting and which were therefore discarded. The compositions of the olivines were deduced from the measured optic axial angles according to the curves given by Winchell (1933, p. 191) with which the data quoted by Bowen and Schairer (1935) are substantially in agreement. Means for the accurate determination of refractive indices permitting a closer approximation to the composition of the pyroxenes (see Figure 6) were not available.

The rocks studied were:—

(a) Basalts selected by Professor J. A. Bartrum as illustrative of the Pleistocene and sub-Recent olivine-basalts of the Auckland urban district and its vicinity as described by Firth (1930, pp. 112–120), Bartrum and Branch (1936, p. 404).

(b) A series of Late Cainozoic basalts and olivine-andesites selected by Professor R. Speight as representative of those of the Lyttelton volcano, Banks' Peninsula, as described by him (Speight, 1924, 1936). They are invaded by a series of trachytic dykes (Speight, 1936, pp. 307–10).

(c) The Pliocene dolerites, basalts, trachybasalts, trachyandesites, kaiwekites [= hybrid olivine-trachytes (?)] and phonolites of the Dunedin district, now under investigation by one of us (W.N.B.), and including many rocks described by Marshall (1906, 1914), to whom we are especially indebted for the use of the slides illustrating his study (1914) of the series of flows on North Head.

## List of Sections Examined.

In the following list the number appearing on the slide label is given in brackets. References are also given to published analyses and descriptions where available.

*Auckland.*

1. Olivine-basalt; Karaka quarry, N. side of Paerata College, Auckland.
2. Olivine-basalt; Smeed's quarry, left bank of Waikato between Tuakau and Mercer, Auckland. Possibly represented by analysis No. 18, *N.Z. Geological Survey Bulletin*, No. 28, p. 70.
3. Olivine-basalt; Smaile's quarry, Takapuna, Auckland.
4. Olivine-basalt; Wiri Mountain, Auckland.
5. Olivine-basalt; West side of Ihumatea Mountain, Auckland.
6. Olivine-basalt; Little Rangitoto, Auckland.
7. Olivine-basalt; Rangitoto Island, Auckland.
8. Olivine-basalt; Urquhart's quarry, Patumahoe, Auckland.

*Banks' Peninsula.*

9. Olivine-basalt; Point Halswell quarry, Banks' Peninsula. For analysis see Speight, 1924, p. 252, No. 1.

10. Doleritic basalt; Dyer's Pass Road, Banks' Peninsula.
11. Olivine-basalt; Ahuriri Lagoon, Banks' Peninsula. For analysis see Speight, 1924, p. 252, No. 2.
12. Olivine-andesite; Garland's quarry, Banks' Peninsula.

*Dunedin District.*

13. Olivine-basalt; Flow No. 4, Otago North Head, Dunedin [Q4]. For analysis see Marshall, 1914, p. 394, No. 4.
14. Olivine-basalt; Otago North Head, Dunedin [Q9]. For analysis see *ibid.*, No. 6.
15. Basalt with little olivine; Flow. No. 10, Otago North Head, Dunedin [Q14]. For analysis see *ibid.*, No. 10.
16. Olivine-basalt; Flow No. 11, Otago North Head, Dunedin [Q15]. For analysis see *ibid.*, No. 11.
17. Basalt with little olivine; Flow No. 16, Otago North Head, Dunedin [Q22]. For analysis see *ibid.*, p. 395, No. 16.
18. Basalt with little olivine; Flow No. 17, Otago North Head, Dunedin [Q23]. For analysis see *ibid.*, p. 395, No. 17.
19. Basalt with little olivine; Flow No. 23, Otago North Head, Dunedin [Q31]. For analysis see *ibid.*, p. 395, No. 23.
20. Olivine-basalt; East of Waironga, Dunedin [KI 3a, N.Z. Geological Survey].
21. Olivine-basalt; South of Jeffreys Hill, Dunedin [KI 29, N.Z. Geological Survey].
22. Olivine-dolerite; Nichol's Creek, Dunedin.
23. Olivine-dolerite; Kaikorai, Dunedin [42]. For analysis see Appendix.
24. Basanite; Mihiwaka, Dunedin [Q27].
25. Trachybasalt with little olivine; Dunedin [P89].
26. Trachybasalt with little olivine; Nevis St., Kaikorai, Dunedin [44]. For description (as andesite) see Marshall, 1906, p. 408. For analyses see Appendix.
27. Olivine-trachyandesite; Anderson's Bay, Dunedin [948].
28. Augite-trachyandesite; conglomerate, Otago North Head, Dunedin [N9].
29. Augite-trachyandesite; North-East Valley, Dunedin [P81].
30. Augite-trachyandesite; Bell Hill, Dunedin [D26]. For description (as augite-diorite or essexite) see Marshall, 1906, pp. 394, 422. For analysis see Appendix.
31. Phonolitic trachyandesite; Robin Hood quarry, Boys' High School, Dunedin [P69].
32. Trachyandesite; Dunedin [Ob 27].
33. Kaiwekite; Dunedin [H16]. For description and comparable analyses see Marshall, 1906, p. 400; 1914, pp. 390, 395; also Appendix.
34. Kaiwekite; Dunedin [D11].
35. Kaiwekite; Kaikai Beach, Dunedin [552].
36. Phonolite; Mopanui, Dunedin [D14]. For description and analysis see Marshall, 1906, p. 405.
37. Phonolite; Purakanui, Dunedin [I7]. For description and analysis see Marshall, 1906, p. 402.
38. Phonolite; Dunedin [4, Auckland University College].
39. Phonolite; Railway-cutting, Blueskin, Dunedin [P24].

## Pyroxenes in Auckland Basalts.

| Rock Number. | Variety. | Mode of Occurrence. | 2V. | Sign. | Remarks. |
|---|---|---|---|---|---|
| 1 | Colourless augite | Small phenocrysts | 62° | + | |
| 1 | Colourless augite | Groundmass | 50 | + | Subophitic |
| | | | 51 | + | |
| | | | 52 | + | |
| | | | 54 | + | |
| | | | 64 | + | |
| 2 | Titan-augite | Zoned phenocryst | 62–58* | + | |
| 2 | Titan-augite | Groundmass | 49 | + | |
| | | | 58 | + | |
| | | | 62 | + | |
| 3 | Titan-augite | Small phenocrysts | 50 | + | |
| | | | 64 | + | |
| 3 | Titan-augite | Groundmass | 60 | + | |
| | | | 62 | + | |
| 4 | Augite | Small phenocryst | 50 | + | |
| 4 | Augite | Groundmass | 54–47 | + | |
| | | | 52 | + | |
| | | | 52 | + | |
| | | | 52 | + | |
| 5 | Titan-augite | Zoned phenocryst | 52–46 | + | |
| 5 | Titan-augite | Groundmass | 52 | + | |
| | | | 59 | + | |
| 6 | Titan-augite | Phenocrysts | 54–67° | + | Hour-glass structure |
| | | | 52–60 | + | |
| 6 | Titan-augite | Zoned phenocryst | 62–46 | + | |
| 6 | Titan-augite | Unzoned phenocrysts | 45 | + | |
| | | | 62 | + | |
| 6 | Titan-augite | Groundmass | 62 | + | |
| 7 | Augite | Phenocrysts | 52 | + | |
| | | | 53 | + | |
| 7 | Augite | Groundmass | 46 | + | |
| | | | 49 | + | |
| | | | 50 | + | |
| | | | 50 | + | |
| | | | 58 | + | |
| | | | 60 | + | |
| 7 | Enstatite | Groundmass | 72 | + | |
| 7 | ? Hypersthene | Groundmass | 88 | — | Possibly Olivine |
| 8 | Augite | Phenocryst | 54 | + | |
| 8 | Augite | Groundmass | 46 | + | |
| | | | 48 | + | |
| | | | 60 | + | |
| Mean | Augite | Phenocrysts | 55 | + | 14 measurements |
| Mean | Augite | Groundmass | 54 | + | 26 measurements |
| Mean | Enstatite | Groundmass | 72 | + | 1 measurement |

* In the case of zoned crystals the first figure refers to the central zone, the second figure to the marginal zone.

## PYROXENE IN LYTTELTON BASALTS AND OLIVINE-ANDESITES.

| Rock Number. | Variety. | Mode of Occurrence. | 2V. | Sign. | Remarks. |
|---|---|---|---|---|---|
| 9 | Augite | Groundmass | 60° | + | |
| | | | 62 | + | |
| 9 | Ortho-pyroxene | Groundmass | 82 | + | Slender prisms |
| | | | 84 | — | |
| 10 | Titan-augite | Zoned phenocrysts | 50–46 | + | |
| | | | 64–60 | + | |
| 10 | Titan-augite | Unzoned phenocryst | 52 | + | |
| 10 | Titan-augite | Groundmass | 52 | + | |
| | | | 54 | + | |
| | | | 56 | + | |
| 11 | Augite | Zoned phenocrysts | 57–65 | + | |
| | | | 50–60 | + | |
| 11 | Augite | Groundmass | 51 | + | |
| | | | 62 | + | |
| 12 | Colourless augite | Phenocrysts | 50 | + | |
| | | | 55 | + | |
| 12 | Colourless augite | Groundmass | 62 | + | |
| Mean | Augite | Phenocrysts | 55 | + | 7 measurements |
| Mean | Augite | Groundmass | 57 | + | 8 measurements |
| Mean | Ortho-pyroxene | Groundmass | 89 | + | 2 measurements |

## PYROXENE IN DUNEDIN BASALTS.

| Rock Number. | Variety. | Mode of Occurrence. | 2V. | Sign. | Remarks. |
|---|---|---|---|---|---|
| 13 | Titan-augite | Phenocrysts | 48° | + | |
| | | | 50 | + | |
| | | | 54 | + | |
| 13 | Titan-augite | Groundmass | 45 | + | |
| | | | 46 | + | |
| | | | 50 | + | |
| | | | 50 | + | |
| 13 | Hypersthene | Groundmass | 72 | — | |
| 14 | Augite | Phenocrysts | 50 | + | |
| | | | 52 | + | |
| 15 | Titan-augite | Zoned phenocrysts | 44 | + | Same value in all zones |
| | | | 46 | + | |
| 15 | Titan-augite | Groundmass | 64 | + | |
| | | | 66 | + | |
| | | | 68 | + | |
| 16 | Titan-augite | Phenocryst | 54 | + | |
| 16 | Titan-augite | Groundmass | 42 | + | |
| 17 | Augite | Phenocrysts | 38 | + | |
| | | | 44 | + | |
| | | | 52 | + | |
| | | | 64 | + | |
| 17 | Augite | Groundmass | 56 | + | |
| 17 | Ortho pyroxene | Groundmass | 86 | + | |
| | | | 89 | + | |
| | | | 90 | | |
| | | | 90 | | |
| | | | 76 | — | Prisms with positive elongation |
| | | | 78 | — | |
| | | | 78 | — | |
| 18 | Augite | Phenocrysts | 51 | + | |
| | | | 54 | + | |
| 18 | Ortho-pyroxene | Groundmass | 76 | — | |
| | | | 77 | — | |
| | | | 80 | — | |
| 19 | Augite | Phenocrysts | 52 | + | |
| | | | 56 | + | |
| 19 | Augite | Groundmass | 56 | + | |
| 19 | Ortho-pyroxene | Groundmass | 84 | — | |
| 20 | Titan-augite | Zoned phenocryst | 50–44 | + | |
| 20 | Titan-augite | Unzoned phenocryst | 62 | + | |
| 20 | Augite | Groundmass | 53 | + | |
| | | | 58 | + | |
| | | | 62 | + | |
| 21 | Hypersthene | Small phenocrysts | 72 | — | Groundmass. Pyroxene is indeterminate (very fine-grained) |
| | | | 72 | — | |
| | | | 72 | — | |
| | | | 72 | — | |
| | | | 88 | — | |
| 22 | Titan-augite | Zoned phenocryst | 52–46 | + | Ophitic dolerites |
| | | Unzoned phenocryst | 46 | + | |
| 22 | Titan-augite | Groundmass | 58 | + | |
| 22 | Enstatite | Groundmass | 78 | + | |
| 23 | Titan-augite | Groundmass | 45 | + | |
| | | | 50 | + | |
| | | | 50 | + | |
| Mean | Augite | Phenocrysts | 50.5 | + | 20 measurements |
| Mean | Augite | Groundmass | 55 | + | 17 measurements |
| Mean | Ortho-pyroxene | Groundmass and small phenocrysts | 81 | — | 18 measurements |

### PYROXENE IN DUNEDIN BASANITES, TRACHYBASALTS, AND TRACHYANDESITES.

| Rock Number. | Variety. | Mode of Occurrence. | 2V. | Sign. | Remarks. |
|---|---|---|---|---|---|
| 24 | Titan-augite | Phenocrysts | 48°<br>49 | +<br>+ | Basanite |
| 24 | Pale green augite | Phenocryst | 70 | + | |
| 24 | Pale green augite with colourless rim | Zoned phenocryst | 70–53 | + | |
| 24 | Bright green augite | Phenocryst | 82 | + | |
| 25 | Titan-augite | Groundmass | 48<br>52 | +<br>+ | |
| 25 | Titan-augite | Phenocrysts | 50<br>50<br>51<br>52 | +<br>+<br>+<br>+ | Trachybasalts |
| 25 | Very pale green augite. | Phenocryst | 68 | + | |
| 25 | Enstatite | Small phenocryst | 76 | + | |
| 25 | Hypersthene | Groundmass | 66<br>72 | —<br>— | |
| 26 | Titan-augite | Zoned phenocrysts | 68–60<br>58–50 | +<br>+ | |
| 26 | Titan-augite | Unzoned phenocrysts | 56<br>60 | +<br>+ | |
| 26 | Titan-augite | Groundmass | 56<br>57 | +<br>+ | |
| 27 | Titan-augite | Phenocrysts | 62 | + | Trachyandesites |
| 28 | Titan-augite | Phenocrysts | 46<br>54<br>58 | +<br>+<br>+ | |
| 28 | Titan-augite | Groundmass | 60<br>60 | +<br>+ | |
| 29 | Colourless augite | Phenocryst | 57 | + | |
| 29 | Colourless augite | Groundmass | 60 | + | |
| 30 | Colourless augite | Groundmass | 46<br>48<br>48<br>58 | +<br>+<br>+<br>+ | |
| 32 | Colourless augite | Phenocryst | 52 | + | |

### PYROXENE IN DUNEDIN KAIWEKITES AND PHONOLITES.

| Rock Number. | Variety. | Mode of Occurrence. | 2V. | Sign. | Remarks. |
|---|---|---|---|---|---|
| 33 | Very pale green augite | Phenocrysts | 58°<br>60<br>68 | +<br>+<br>+ | Kaiwekites |
| 33 | Very pale green augite | Groundmass | 54 | + | |
| 34 | Colourless augite | Phenocrysts | 50<br>52<br>58<br>68 | +<br>+<br>+<br>+ | |
| 35 | Very pale green augite | Phenocrysts | 59<br>60 | +<br>+ | |
| 35 | Very pale green augite | Groundmass | 62 | + | |
| 36 | Green aegirine-augite | Phenocryst | 72 | + | Rimmed with optically negative aegirine |
| 37 | Colourless augite | Central zones of phenocrysts | 46<br>56 | +<br>+ | |
| 37 | Deep green aegirine | Outer zones of same phenocrysts | 80<br>70 | —<br>— | |
| 38 | Titan-augite | Phenocryst | 62 | + | Rimmed with aegirine |
| 39 | Titan-augite | Central zones of phenocrysts | 48<br>50 | +<br>+ | |
| 39 | Deep green aegirine | Outer rim of second phenocryst | 75 | — | |

## OLIVINE IN AUCKLAND BASALTS.

| Rock Number. | 2V. | Sign. | Remarks. |
|---|---|---|---|
| 1 | 88–84° | — | Outer zone (84) narrow |
| | 86 | — | |
| 2 | 86 | + | |
| | 88 | — | |
| | 90–85 | — | Outer zone narrow |
| | 84–88 | — | Outer zone narrow |
| 3 | 84 | — | |
| | 86 | — | |
| | 88 | — | |
| 4 | 87 | — | |
| | 90–84 | — | Outer zone narrow |
| | 86–90 | — | Outer zone narrow |
| 5 | 88 | + | |
| | 88 | + | |
| | 90 | | |
| | 88 | — | |
| | 86 | — | |
| 6 | 88 | — | |
| | 78 | — | |
| | 78 | — | |
| 7 | 82 | — | |
| | 80 | — | |
| | 76 | — | |
| 8 | 88 | — | |
| | 84 | — | |
| | 82 | — | |
| Mean of 26 measurements | 86° | — | |

Mean Composition: 77% Forsterite.
Range in Composition: 97% to 55% Forsterite.

## OLIVINE IN LYTTELTON BASALTS AND OLIVINE-ANDESITES.

| Rock Number. | 2V. | Sign. | Remarks. |
|---|---|---|---|
| 9 | 80° | — | |
| | 86 | — | |
| 10 | 85 | — | $\gamma-\alpha = 0{\cdot}035$ (measured on a second grain) |
| 11 | 86 | + | |
| | 87 | + | |
| | 89 | + | |
| | 89 | + | |
| | 90 | | |
| 12 | 70 | — | |
| | 70 | — | |
| | 72 | — | |
| Mean of 11 measurements | 84 | — | |

Mean Composition: 72% Forsterite.
Range in Composition: 97% to 42% Forsterite.

### OLIVINE IN DUNEDIN BASALTS.

| Rock Number. | 2V. | Sign. |
|---|---|---|
| 13 | 82° | — |
|  | 90 |  |
| 14 | 86 | — |
| 16 | 80 | — |
|  | 84 | — |
| 20 | 88 | — |
|  | 88 | + |
| 21 | 80 | — |
|  | 82 | — |
| 22 | 84 | — |
|  | 86 | + |
| 23 | 84 | + |
|  | 88 | + |
| Mean of 13 measurements | 87 | — |

Mean Composition: 79% Forsterite.

Range in Composition: 100% to 63% Forsterite.

### OLIVINE IN DUNEDIN BASANITE, TRACHYBASALTS AND TRACHYANDESITES.

| Rock Number. | 2V. | Sign. | Remarks. |
|---|---|---|---|
| 24 | 76° | — | Basanite |
|  | 86 | — |  |
|  | 90 |  |  |
| 25 | 76 | — | Trachybasalt |
| 27 | 60 | — | Trachyandesites |
|  | 66 | — |  |
| 31 | 89 | — |  |
| Mean of 7 measurements | 78 | — |  |

Mean Composition: 59% Forsterite.

Range of Composition: 87% to 24% Forsterite.

### OLIVINE IN DUNEDIN KAIWEKITES AND PHONOLITES.

| Rock Number. | 2V. | Sign. | Remarks. |
|---|---|---|---|
| 33 | 65° | — | $\gamma-\alpha = 0.047$ for a second crystal<br>Kaiwekites |
| 34 | 82 | — |  |
| 35 | 83 | — |  |
| 36 | 90 |  | Phonolites |
|  | 88 | + |  |
| 37 | 88 | + |  |
| 38 | 89 | — |  |

## DISCUSSION.

Barth (1931) found that the optic axial angle 2V in phenocrystic pyroxene in Pacific basalts was uniformly about 58°, the range 54°–60° being exceeded only in the case of an olivinic sub-basalt from the Marquesas (51°). In zoned pyroxenes the consistently small optic axial angles and higher refringence of the outer zones indicated that with advancing crystallisation the pyroxene tended to become richer in iron but poorer in lime. The groundmass pyroxene is more variable. In the majority of the sub-basalts the optic axial angles varied between the above limits, but in the minority they were nearer 40° and in one case as low as 20°, indicating the presence of pigeonitic pyroxene [defined as possessing $2V < 50°$ (Barth, 1931a) or $< 45°$ (Kuno, 1936)]. In one sub-basalt from the Marquesas and in an oceanite associated therewith, pyroxenes with $2V = 80°$ and 75° respectively were noted (suggesting the presence of either alkaline or orthorhombic pyroxene, though Barth does not draw either inference). In the saturated basalts, half of the groundmass pyroxenes have $2V = 40°–50°$ and the remainder $2V = 10°–40°$. In the plateau basalts of Greenland, Iceland, the Faroes, Spitzbergen and the Deccan, the pyroxenes are almost uniformly pigeonite (Barth, 1936, and authors cited therein).

Tsuboi (1832) showed that in the saturated andesites of Japan the phenocrysts are normally hypersthene and augite, and the groundmass-pyroxene pigeonite. Kuno noted that pigeonitic phenocrysts occur rarely, and that augite and hypersthene may be present together in the groundmass. Tsuboi concluded that the first two types of pyroxene are only partially miscible in the intratelluric stage of slow cooling, though completely miscible in the effusive stage.

Kuno, extending Barth's evidence for increasing concentration of $FeSiO_3$ in the magma during the crystallisation of the pyroxene, held that the course of crystallisation depended on the total composition of the normative pyroxene in the magma. If it lay on the magnesian side of a line joining $CaSiO_3$ (=Wo) to the point $En_{52}Fs_{48}$ on a triangular diagram, intratelluric crystallisation commenced with the formation of diopside and/or hypersthene (according to the composition in regard to Tsuboi's " two-pyroxene boundary "). (See Fig. 6.) This might be followed by formation of pigeonite (zonally about the diopside, or intergrown with or making over the hypersthene), when by increasing concentration of $FeSiO_3$ the composition of the magmatic pyroxene had entered the pigeonite-field. In the quickly cooling effusive stage the groundmass pyroxene might be diopside and hypersthene, but was more usually pigeonite. Should, however, the normative pyroxene in the initial magma show a pigeonitic composition, that type of pyroxene will crystallise directly either on rapid or slow cooling. These conclusions, it is held, are in general accord with Bowen and Schairer's (1935) deductions from their experimental work.

Kennedy (1933) drew a sharp distinction between the nature of pyroxene in olivine-basalts and tholeiites. The former, he held, gave rise to quartzless alkaline differentiates, trachyandesite, trachyte and phonolite, and possessed only diopsidic pyroxene- [exceptions to this had been described by Barth (1931)]; the tholeiites gave rise to andesites, dacites, and rhyolites, and contained chiefly pigeonitic pyroxenes. "In undersaturated basalts (such as those studied by Barth) it is shown that the profuse early crystallisation of olivine so enriches the residual liquid in lime relatively to magnesia and iron that when the pyroxene begins to crystallise it does so in a diopsidic variety, whereas in the over-saturated basalts or basic andesites (similar to the types studied by Tsuboi) no olivine or only a little olivine separates out, and early crystallisation of pyroxene will take place with the formation of a relatively lime-poor pigeonitic variety" (Tyrrell, 1937). The last author (*loc. cit.*) has described the pyroxene phenocrysts in an Antarctic limburgite as "pale brown almost colourless or even faint green diopside with 2V = 60°, whereas the groundmass pyroxene together with the narrow margins of the phenocrysts consist of purple titanaugite with 2V about 15°–20°."

Barth's (1931) studies of optic axial angles of olivines in Pacific lavas indicate a moderate variation in composition, with a tendency to become richer in iron with decreasing basicity of the enclosing rock. In the sub-basalts it rarely exceeds the limits, forsterite 78% to 87%, and averages 84%. The average composition of olivines in pacificites and saturated basalts (and also the only olivine-phonolite noted) is 80% forsterite.

With this summary we may compare the results of the present investigation.

## CONCLUSIONS.

In Dunedin basalts pyroxene usually occurs in two generations. The large phenocrysts are always diopsidic titan-augite. When zonary structure is shown the outer zones sometimes appear to be richer in clinoenstatite than the core. While this agrees with Barth's observations it does not accord with the experimental work of Bowen (1928, pp. 49–52) on the system diopside-forsterite-silica. In the groundmass diopsidic titanaugite may be associated with orthorhombic pyroxene, and in a few instances the latter only was observed. In one example hypersthene forms small phenocrysts (No. 21). The appearance of augite and hypersthene as separate mutually associated phases in Dunedin basalts, suggests that the temperature of crystallisation of the groundmass may be lower than is normal in basaltic lava; unusual richness in volatile constituents is certainly indicated by plentiful deuteric siderite in many of the Dunedin rocks. Pigeonite as defined by Kuno (2V $< 45°$) occurs but rarely, notably as phenocrysts in No. 17 (normative pyroxene = $Wo_{37}En_{39}Fs_{24}$). Transitional types of pyroxene which would be classed as pigeonite (2V < 50°) by Barth occur in No. 15 as phenocrysts in a groundmass of normal augite (normative pyroxene = $Wo_{43}En_{35}Fs_{22}$), and both as phenocrysts and in the groundmass of No. 13 (normative pyroxene = $Wo_{36}En_{33}Fs_{31}$).

The usual pyroxenes recorded in the more alkaline rocks of the Dunedin district (trachyandseites, kaiwekites and phonolites) are diopsidic augite, aegirine-augite and aegirine. In one section of trachybasalt (No. 25) orthorhombic pyroxene is plentiful. In No. 26, decrease in axial angle from the central zones outward in crystals of titan-augite was noted.

In the basalts of Auckland and the Late Tertiary basalts of Banks' Peninsula, diopsidic augite is almost always the only pyroxene present. Orthorhombic pyroxene was recorded in one rock from Banks' Peninsula (No. 9) and in one from Auckland (No. 7); in both cases it is associated with normal augite which in No. 7 is also accompanied by augite approaching pigeonite in composition. When phenocrysts show zonary structure the clinoenstatite content usually increases from within the crystal outwards, but the reverse condition was noted in two rocks (Nos. 6 and 11).

Olivine is more plentiful in the basalts of Auckland than in most Banks' Peninsula or Dunedin basalts. The mean compositions for olivines from the three localities, as deduced from the axial angle, are: Auckland, 77% forsterite; Banks' Peninsula, 72% forsterite; Dunedin, 79% forsterite. The relatively low figure for the Lyttelton mineral is due to inclusion of three measurements made on iron-rich olivines (forsterite, 45%) in an olivine-andesite.

In the basanites, trachybasalts and trachyandesites of Dunedin the iron-content of the olivine is generally higher than in basaltic olivine, the percentage of forsterite in one instance being as low as 24% (No. 27). In one of the three kaiwekites examined pale-yellow iron-rich olivine (24–32% forsterite) was also noted. In the two remaining kaiwekites (Nos. 34 and 35) the forsterite content of the olivine is about 70%.

The olivine of three typical olivine-phonolites from Dunedin is consistently magnesian (forsterite 85–90%). It occurs as xenocrystic clusters rimmed with aegirine. Small xenoliths of olivine basalt are common in such rocks.

The writers wish to record their thanks to Professors J. A. Bartrum and R. Speight for loan of material from Auckland and Lyttelton respectively; and to Dr. P. Marshall for the original material from Otago North Head.

## APPENDIX.

The following hitherto unpublished analyses of rocks containing minerals described in the foregoing were made by Mr. F. T. Seelye, F.I.C., to whom and to the Directors of the Dominion Laboratory and the Geological Survey the authors' thanks are due.

| Rock No. | 23 | 26 | 30 | 31 | 33 |
|---|---|---|---|---|---|
| $SiO_2$ .. | 45.77 | 52.37 | 57.88 | 56.22 | 58.53 |
| $Al_2O_3$ .. | 12.98 | 18.49 | 18.07 | 18.56 | 16.17 |
| $Fe_2O_3$ .. | 3.17 | 2.53 | 2.22 | 2.57 | 3.78 |
| FeO .. | 8.86 | 5.17 | 2.54 | 2.95 | 2.70 |
| MgO .. | 16.00 | 2.34 | 0.83 | 1.03 | 1.28 |
| CaO .. | 9.67 | 5.25 | 3.94 | 3.51 | 3.44 |
| $Na_2O$ .. | 2.33 | 5.47 | 5.77 | 7.20 | 5.66 |
| $K_2O$ .. | 0.83 | 3.20 | 3.94 | 4.59 | 4.51 |
| $K_2O+$ .. | 0.98 | 1.06 | 1.02 | 0.86 | 1.24 |
| $H_2O-$ .. | 0.40 | 1.59 | 0.77 | 0.78 | 0.85 |
| $CO_2$ .. | 0.10 | 0.03 | 0.43 | 0.10 | 0.49 |
| $TiO_2$ .. | 2.05 | 1.27 | 1.55 | 0.87 | 0.80 |
| ZnO .. | Nt. fd. | Nt. fd. | 0.06 | Nt. fd. | 0.03 |
| $P_2O_5$ .. | 0.40 | 0.46 | 0.56 | 0.36 | 0.26 |
| S .. | 0.02 | 0.05 | 0.02 | Tr. | 0.03 |
| Cl .. | 0.01 | 0.09 | Tr. | 0.17 | 0.03 |
| $Cr_2O_3$ .. | 0.07 | Nt. fd. | Nt. fd. | Nt. fd. | Nt. fd. |
| $V_2O_5$ .. | 0.03 | — | — | — | — |
| MnO .. | 0.20 | 0.23 | 0.11 | 0.18 | 0.16 |
| NiO .. | 0.04 | 0.02 | Tr. | Nt. fd. | Tr? |
| BaO .. | 0.02 | 0.09 | 0.10 | 0.11 | 0.12 |
| SrO .. | 0.04 | 0.02 | 0.03 | Tr. | 0.01 |
|  | 99.97 | 99.73 | 99.84 | 100.06 | 100.19 |
| O for Cl .. |  | .02 |  | .04 | .01 |
|  | 99.97 | 99.71 | 99.84 | 100.02 | 100.18 |

23. Olivine Dolerite (Slide No. 42), Farley Street, Kaikorai, Dunedin.
26. Trachybasalt (Slide No. 44), Nevis Street, Kaikorai, Dunedin.
30. Trachyandesite (Slide No. 401), at depth of 250ft. in bore 50 yards W. Dunedin Railway Station.
31. Phonolitic Trachyandesite (Slide No. 70), Robin Hood Quarry, Otago Boys' High School, Dunedin.
33. Kaiwekite (Slide No. 680), Te Whakareka-iwi, Otago Peninsula.

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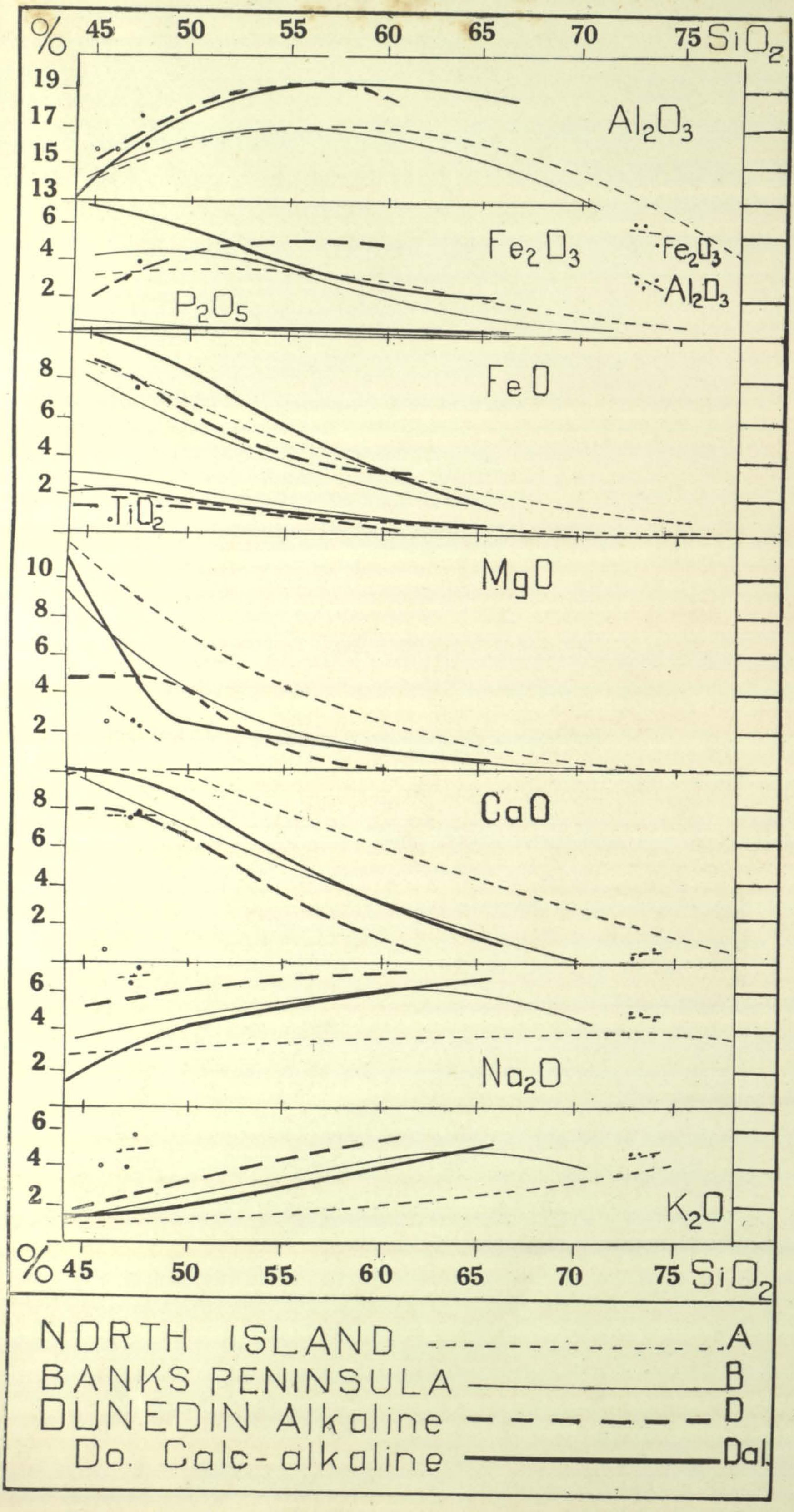

FIG. 1.—Smoothed composition variation diagram for New Zealand Cainozoic lavas.

*To face page 72.*

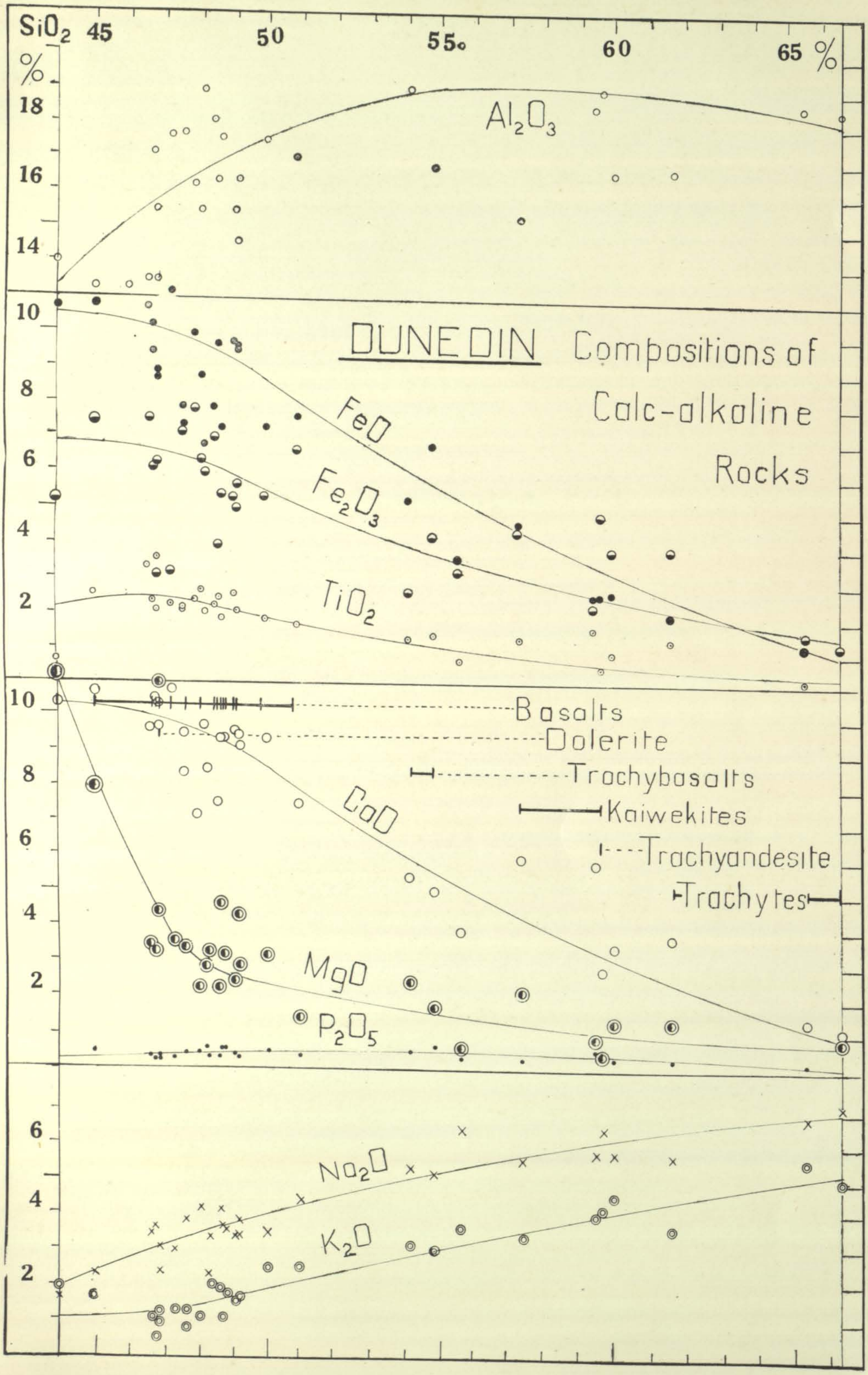

Fig. 2.—Calc-alkaline rocks, Dunedin district.

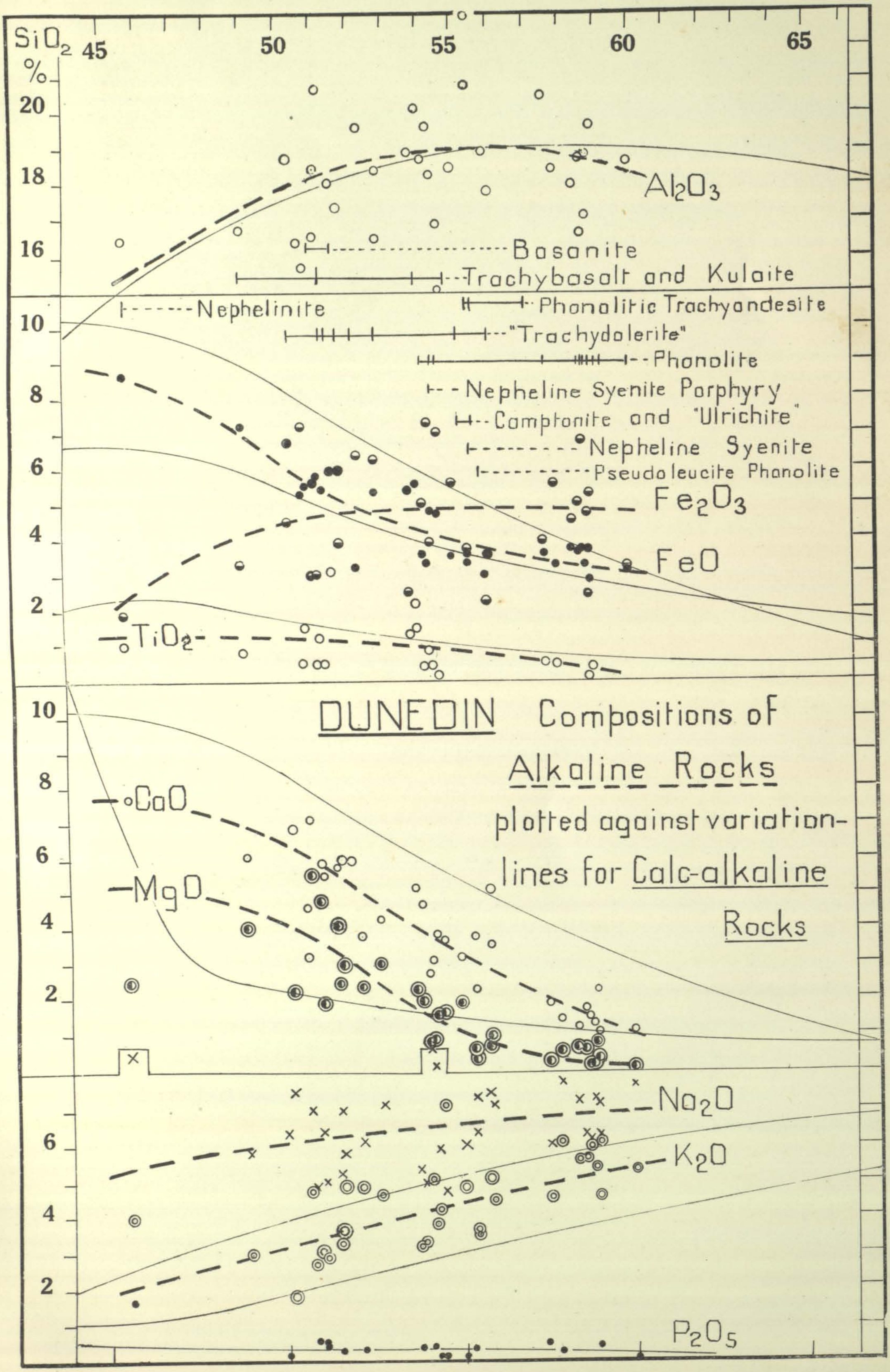

FIG. 3.—Alkaline rocks, Dunedin district.

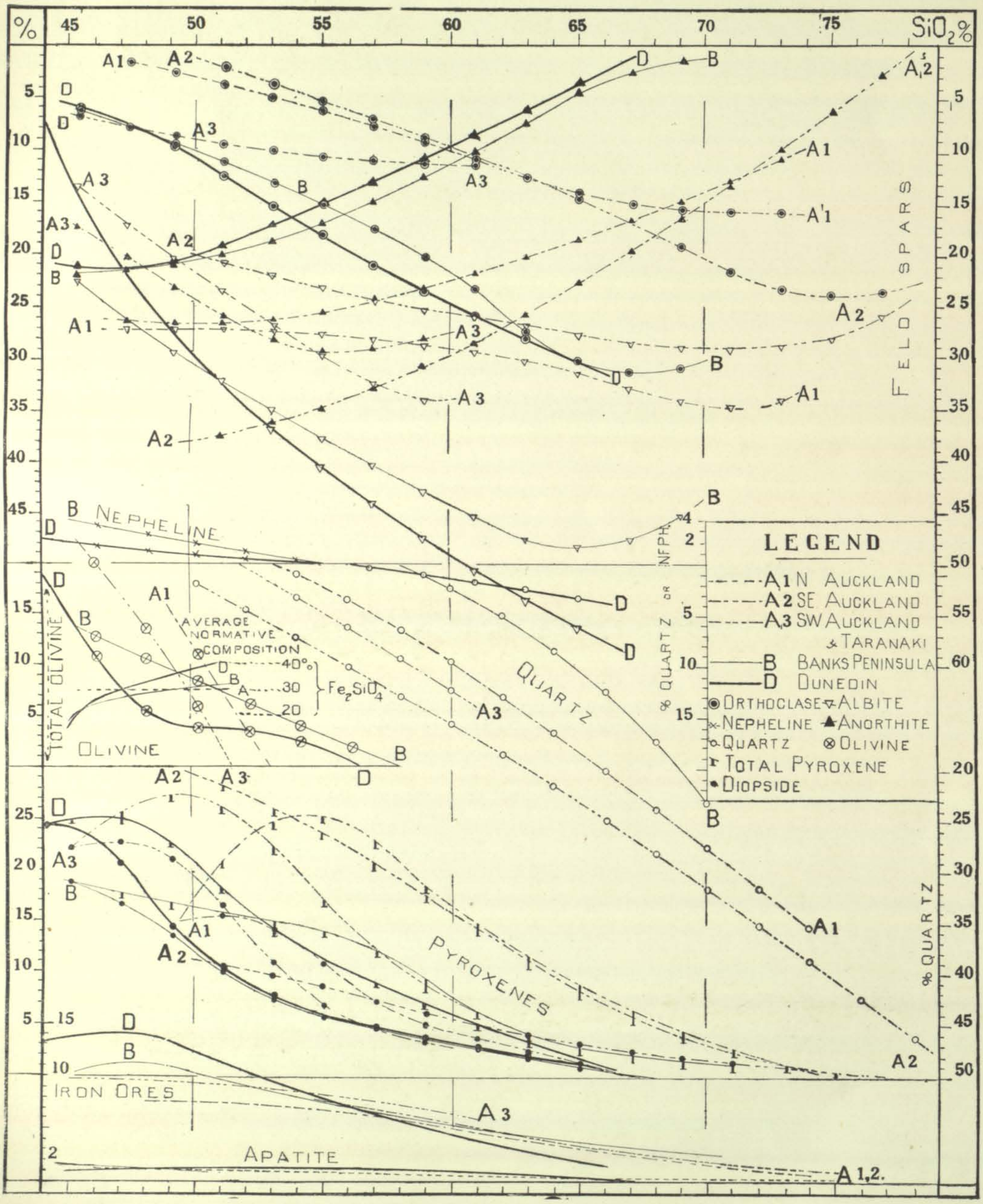

Fig. 4.—Norm-variation diagram for New Zealand calc-alkaline Cainozoic Volcanic Rocks.

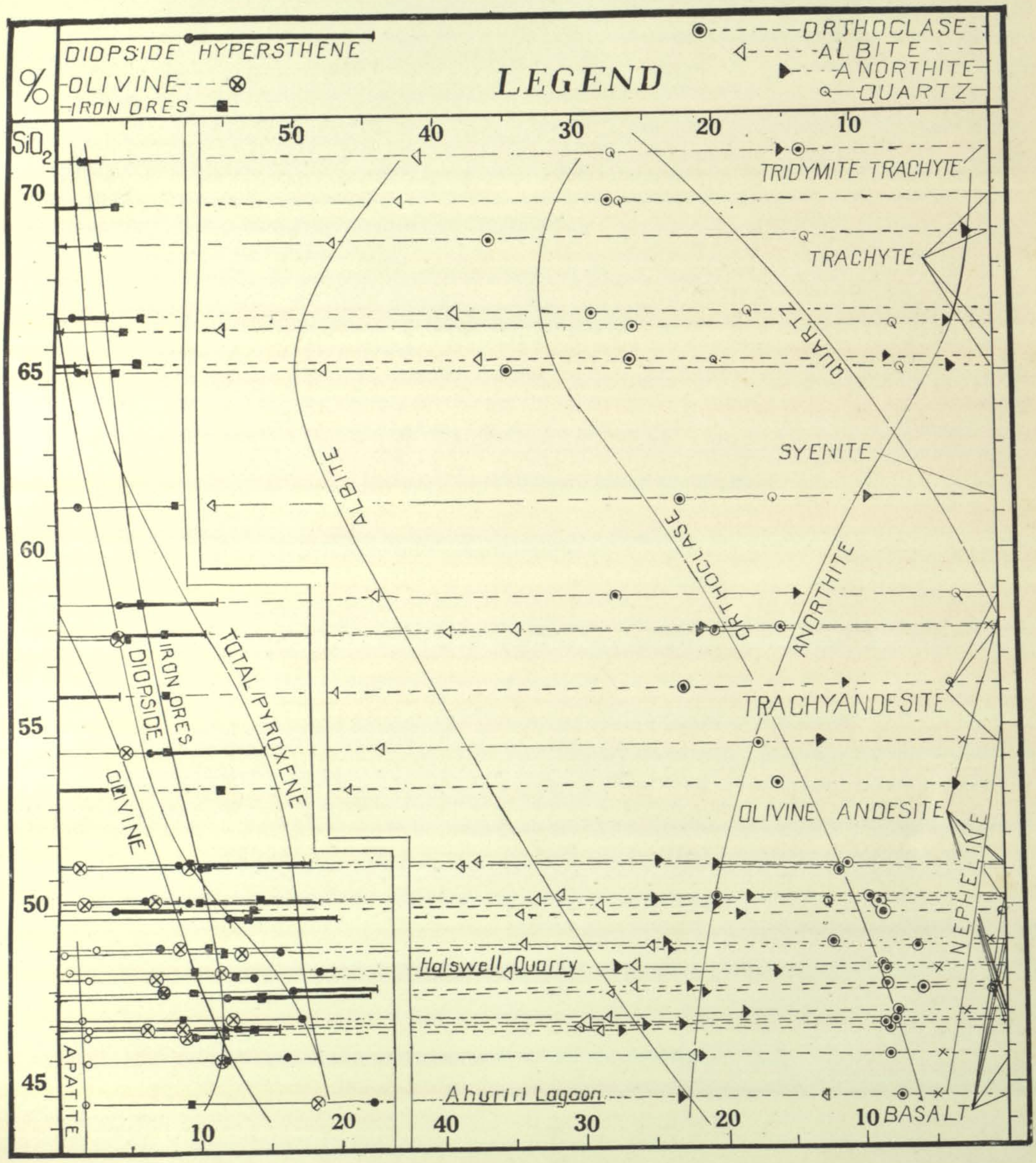

Figure 5.

*To follow plate 4.*