

The chemical composition and physical properties of the residual glass of the Kap Daussy tholeiite dike, east Greenland.

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Introduction.

IN the course of a petrological examination of some hundreds of specimens from the Tertiary coastal dike swarm of east Greenland, collected at various times by L. R. Wager and W. A. Deer, it was decided to investigate the nature of the residual glassy mesostasis of one of the olivine-tholeiites, in the hope that it might shed some light on the trend of differentiation of the magma responsible for the bulk of the rocks in the swarm. An account of the petrology of the swarm as a whole will be published in due course, but it was thought that a note on the chemical and physical properties of this glassy residuum might be worthy of independent publication, particularly as it provides an interesting comparison with the results of work carried out by Walker (1930, 1935) on the residual glass from one of the Upper Carboniferous tholeiites from central Scotland. The general features of the east Greenland coastal dike swarm have already been described by Wager and Deer (1938) and Wager (1947).

The Kap Daussy tholeiite.

The particular specimen investigated, which is here called the Kap Daussy tholeiite, was taken from a dike, 20 feet in width, about 300 yards east of the south-west point of Kap Daussy, south-west of Scoresby Sound, in latitude $68^{\circ} 40' N.$, longitude $26^{\circ} 40' W.$ Seven dikes were sampled between the south-west point of Kap Daussy and a point about one mile to the east. All these carry a certain amount of devitrified glass or late crystallized residuum, but the Kap Daussy dike dealt with here is the only one with an appreciable quantity of fresh glass. It cuts, and is chilled against a dike 12 feet wide which is the third dike east of the south-west point of Kap Daussy.

The dike rock itself is a fresh basic rock, with a little olivine and a light brown residual glass, patchy in its distribution and generally showing intersertal texture with respect to the other minerals (fig. 1). In texture, and in mineralogical and chemical composition, the rock closely resembles some of the tholeiites of the Salen type described (Bailey, 1924) from the Mull Tertiary swarm, and the chemical analysis of one of these latter is reproduced, for purposes of comparison, in table I (p. 56). The Kap Daussy rock will be called a tholeiite, cf. Salen type.

In table I are given also the chemical analyses of the Kap Daussy tholeiite (E.G. 1123) and the Kinkell (Dumbartonshire) tholeiite investigated by Walker (1935) together with norms and modes. It will be seen that the Kap Daussy and Mull tholeiites are, on the whole, very similar chemically. The Greenland rock is richer in iron oxides and rather poorer in alumina than the Mull rock, though the sum of these constituents is much the same in both. Titania is also a good deal higher in the Kap Daussy rock, but in all other respects there is close agreement. Physical and chemical data for the residuum of the Mull rock are not given in the Mull memoir, but the similarity in chemical composition with the Greenland rock makes it appear possible that the residua will also be somewhat similar.

The writer is indebted to Dr. K. C. Dunham for providing a chip of this analysed Salen tholeiite (Geol. Surv. S. 16808) from the Survey collection. In the crushed and separated material it is seen that the mesostasis is not a fresh glass as in the Kap Daussy rock, but is practically all altered to palagonitic material very similar to that which is present in small amount in the Kap Daussy rock. One or two fragments of unaltered glass from the Mull rock have a refractive index around 1.50, while the refractive index of the birefringent palagonitic material covers a range from about 1.55 to 1.60.

The analysis of the Kap Daussy rock deviates rather more widely from Walker's Kinkell tholeiite (analysis B) which is considerably richer in total alkalis and in potash and has rather less iron, lime, and magnesia. Titania is high, and alumina also is closer to the figure for the Kap Daussy rock than for the Mull example. Walker (1935) remarks that among the Carboniferous dolerite intrusions of central Scotland the alumina content tends to be rather lower in the tholeiitic rocks (mostly between 11.25 and 12.15 %) than in the associated quartz-dolerites (12.70 to 14.61 % in the examples there cited), and the alumina figure for the Greenland tholeiite under discussion is similarly

rather lower than for other dolerite dikes in the same swarm which have so far been analysed.

Consideration of the calculated norms and measured modes for the Kap Daussy and Kinkell tholeiites (table I) shows at once the acid



FIG. 1. Photomicrograph of the Kap Daussy, east Greenland, tholeiite showing an unusually large area of residual glassy mesostasis with inclusions. Ordinary light. $\times 45$.

nature of the glassy mesostasis. In neither rock does quartz appear as a crystalline phase, yet silica in excess is present to a small extent in the norms of both: indeed, there is 7.6 % of normative quartz in the Kinkell rock, where the amount of residual glass is considerably more than in the Greenland one. The latter actually contains a little olivine (about 4 %), which appears in the norm as hypersthene (together with a little excess silica), because of the silica-rich glass.

The residual glass.

The glass (fig. 1) in the Kap Daussy tholeiite is rather patchily distributed, occurring often, and typically, in small wedge-shaped areas between well-formed laths of plagioclase, giving a typical 'intersertal' texture. It makes up about 20 % by volume (16 % by weight) of the whole rock, though its irregular distribution tends to reduce the accuracy of micrometric analyses. For the most part it is pale brown, clear, and isotropic, but here and there it is partly replaced by green anisotropic material, which is largely chloritic, and presumably formed by devitrification.

A small proportion (perhaps 1-2 % of the glass) is darker orange-brown in colour, and weakly birefringent. This substance—which shows more clearly in the crushed material prepared for analysis than in thin sections of the rock—is probably an oxidized and hydrated product of the glass itself, formed in a manner analogous with the alteration of sideromelane to palagonite.

The glass contains tiny inclusions. These are chiefly apatite, as needles and small prisms, but small crystals of pyroxene, felspar, and occasionally even of olivine, are found.

The concentrate for chemical analysis was prepared as follows. The rock was first crushed to pass a 120-mesh sieve, the finest rock flour washed away, and the powder, after drying at 100° C., was separated into light and heavy fractions with bromoform. The lighter fraction was rubbed gently in an agate mortar to break down as many composite grains as possible, and was then centrifuged in a bromoform-benzene mixture of specific gravity 2.6. This served to sink the felspar and felspar-rich composite grains, leaving a floating fraction rich in glass. By repeating the gentle rubbing and the centrifuging three times, a concentrate was obtained in which the only impurities were a trace of felspar and a few grains of the darker orange palagonitic material referred to above. Chlorite was entirely absent.

Microscope slides of the glass concentrate were prepared, and a grain count confirmed that the contamination by plagioclase in composite grains was certainly less than 2 %. Most of the inclusions of apatite are presumably still present in the glass concentrate, but the larger inclusions of other minerals were effectively removed by the crushing and centrifuging.

It may be mentioned in passing that considerable difficulty was experienced in washing out the last traces of bromoform from the glass

concentrate. Despite repeated washings with benzene and with ether, very slight traces of bromoform could be detected when the material was heated in an ignition tube. This substance must either be adsorbed very tenaciously on to the surface of the glass or else held in tiny cracks. Its presence means that the figure stated for H_2O at 110° in the analysis includes a trace of organic matter, though it is certainly not enough to affect the accuracy of the analysis significantly.

The results of the chemical analysis are given in table II (p. 57), together with others for comparison. The actual analysis of the glass concentrate is given in column IIa; in column II it has been corrected for the presence of 2% of plagioclase of composition $Or_5Ab_{50}An_{45}$ (the value estimated from refractive index measurements) and recalculated to 100.00%. It will be seen that allowance for this maximum estimated contamination of the analysed material by plagioclase makes very little difference indeed to the analysis. The 'corrected' analysis has already been given in table I, and has been used in all the other calculations and diagrams.

The refractive index and specific gravity were measured on the material separated for analysis. The bulk of the glass has a refractive index, determined by the immersion method, of 1.516. The material is not quite uniform, and there is a little variation in refractive index both above and below this figure, which is considered to be a good average. The specific gravity was determined by suspension in bromoform-benzene mixtures. Again, there is some slight variation above and below a central value, but the bulk of the material has a specific gravity of 2.43.

Correlation of physical properties with chemical composition.

The investigations of Tilley (1922) and George (1924) into the relationships between specific gravity, refractive index, and chemical composition of naturally occurring glasses were made on holohyaline rocks, yet it is interesting to see how they fit the results obtained for the Kinkell and Kap Daussy residual glasses. George (1924) has given curves relating refractive index to specific gravity, and refractive index to the content of the more important oxides in natural glasses. The values read from these curves corresponding to the measured refractive indices of the Kap Daussy and Kinkell residual glasses are given below, compared with the actual values obtained by direct chemical analysis.

The agreement is reasonably good, though both residual glasses are richer in lime than the curves would indicate, and the Greenland glass

| | Glass from Kap Daussy tholeiite. | | Glass from Kinkell tholeiite. | |
|--|-------------------------------------|-----------|----------------------------------|-----------|
| | From | From | From | From |
| | George's curves. | analysis. | George's curves. | analysis. |
| SiO ₂ | c. 65 % | 64.0 % | c. 74 % | 66.8 % |
| FeO + Fe ₂ O ₃ ... | 5.5 | 5.8 | 2.5 | 2.5 |
| MgO | 1.5 | 1.2 | 0.4 | 0.5 |
| CaO | 3.5 | 5.6 | 1.2 | 2.6 |
| K ₂ O | 3.8 | 1.5 | 4.1 | 4.2 |
| Sp. gr. | 2.51 | 2.43 | 2.33 | 2.38 |

is, of course, much poorer in potash. The results do suggest, however, that George's published curves may well be used to gain a fair idea of the composition of a residual glass of known refractive index in calc-alkaline rocks of the types here considered.

Tilley (1922) classified natural glasses on the basis of specific gravity and refractive index determinations, and found that by plotting specific gravity against specific refractivity the fields occupied by the various types of natural glasses are clearly delimited. If the specific refractivities ($K = (n-1)/d$) are calculated for the two residual glasses under discussion, and the values plotted on Tilley's curve (fig. 2 in his paper), it is found that the glass from the Kinkell tholeiite falls only just outside the field occupied by the rhyolite obsidians, as might be expected from its composition, while the Kap Daussy glass also falls outside this field, but falls within the field occupied by the 'australites'. These curious representatives of the tektite group of natural glasses are somewhat abnormal in composition, and are considered by many to be of meteoritic origin (cf. Spencer (1939), where all reliable physical and chemical data relating to them are collected together).

Chemical analyses of two tektites quoted from Spencer's paper are included in table II, and it will be seen that the Kap Daussy residual glass, which falls into Tilley's tektite field on the basis of physical properties, is also reasonably comparable in chemical composition. Scrutiny of Spencer's table of analyses shows that tektite glasses with refractive index and specific gravity comparable with the Greenland glass tend also to be relatively impoverished in alkalis and to have a relatively high content of iron oxides: most of this iron is usually in the ferrous state. Terrestrial volcanic glasses are usually chemically distinct from the tektites, and it is therefore of some interest to record the occurrence of a glass of terrestrial origin of closely comparable composition and having similar physical properties.

Tilley (1922) has further shown that a theoretical value for the specific refractivity of a glass can be calculated from the known (or inferred)

specific refractivities of the standard normative minerals in a glassy state. In many of the cases investigated he finds a close correspondence between these 'calculated' values and the 'observed' ones deduced from the measured specific gravity and refractive index ($K_{\text{obs.}} = (n-1)/d$). The discrepancy between observed and calculated values increases with the basicity of the glass and with its tenor of water (which has a high specific refractivity).

Such values have been calculated in the way indicated by Tilley for the two residual glasses, and are given below:

| | K obs. | K calc. | K calc.— K obs. (water free). | K calc. |
|----------------------------------|----------|-----------|--------------------------------------|-----------|
| Kinkell glass | 0.2079 | 0.2211 | 0.0132 | 0.2104 |
| Glass from Kap Daussy tholeiite. | 0.2124 | 0.2228 | 0.0104 | 0.2145 |

It will be noticed that the discrepancy between observed and calculated specific refractivities is of the order of 5 % in both instances, while agreement is really close if the calculation is based on 'water-free' analyses.

Chemistry of the residual glass.

The main features of the chemical analysis of the glass from the Kap Daussy tholeiite are a fairly high silica percentage, combined with low content of alkalis and relatively high content of iron and lime. As might perhaps be expected, the glass is rich in water—indeed the water content of the residual glass accounts for the greater part of the total water in the whole parent rock.

The composition of this glass is unusual. One would expect that it would be fairly comparable with rocks of corresponding silica percentage lying on the line of one or other of the igneous rock suites believed to be derived from the differentiation of a basaltic magma. Yet it is difficult to find analyses of other rocks which provide anything of a close comparison. As has already been mentioned, there is fairly close resemblance with two analyses of tektite glasses (analyses K and L, table II); Washington's tables of analyses (1917) provide only two comparable ones (F and G in table II), of which the dacite-pitchstone from Madagascar provides the closer comparison. From the British Tertiary province, two inninmorite-pitchstones from Mull provide the nearest comparable rocks. The analysis of one of these is given as analysis E in table II (p. 57).

It may perhaps be significant that the few rocks found which are more or less comparable in chemical composition with this residual glass are themselves glassy. This suggests that silicate solutions having these

somewhat unusual compositions may not crystallize very easily, so that a glassy product may be as much a function of chemistry as of the physical conditions obtaining at the time of consolidation.

The glass separated by Walker from the Kinkell tholeiite has more the composition which would be expected of the late differentiate of a basic magma. It is richer in alkalis than the Greenland one and much poorer in iron, lime, and magnesia. Walker remarks that, had it crystallized, the Kinkell glass would probably have yielded a micropegmatite, and in support of this he compares its composition with those of some of the granophyric segregation veins from the local dolerites, and with an acid vein from the Whin Sill (H and J, table II).

The most striking feature of the Kap Daussy glass, on the other hand, is its paucity in alkalis, particularly in soda. In fact there is a little less soda in the glass than in the parent rock, though potash has increased threefold and the total ($K_2O + Na_2O$) is rather higher. Such a glass could scarcely be expected to yield typical micropegmatite on crystallization, when there is only 9 % of normative orthoclase (as against 25 % in the Kinkell glass) and when the proportion of normative femic constituents is so much higher.

In this connexion it is perhaps relevant to remark that in another dike rock (E.G. 1120) from nearly the same locality there is a crystallized late mesostasis, consisting of acicular iron-ore crystals, tiny crystals of very strongly zoned plagioclase, chlorite, and small granules of a pyroxene, together with a little quartz and probably orthoclase in places, though the mesostasis is very fine grained and it is difficult to resolve the various minerals with the microscope. The rock itself is of the same general type as the one under discussion, and the proportion of mesostasis is about the same also. The nature of this crystalline mesostasis seems to indicate that in the earlier stages the residual liquid had still a fair proportion of lime and of iron (the abundance of magnetite indicates a high ratio $Fe_2O_3:FeO$). The strongly zoned plagioclase indicates that the liquid became enriched in soda only towards the very last stages in the crystallization.

The relationship between the chemical compositions of the Kap Daussy and Kinkell tholeiites and their residual glasses is shown diagrammatically in fig. 2. In this diagram the percentage of each oxide (along the ordinate) is plotted against the silica percentages of rock and glass (along the abscissa), cognate pairs of points being joined by arrows. It must be emphasized that these arrows are only 'tie-lines' and that there is no evidence of linear variation of each oxide with increasing silica.

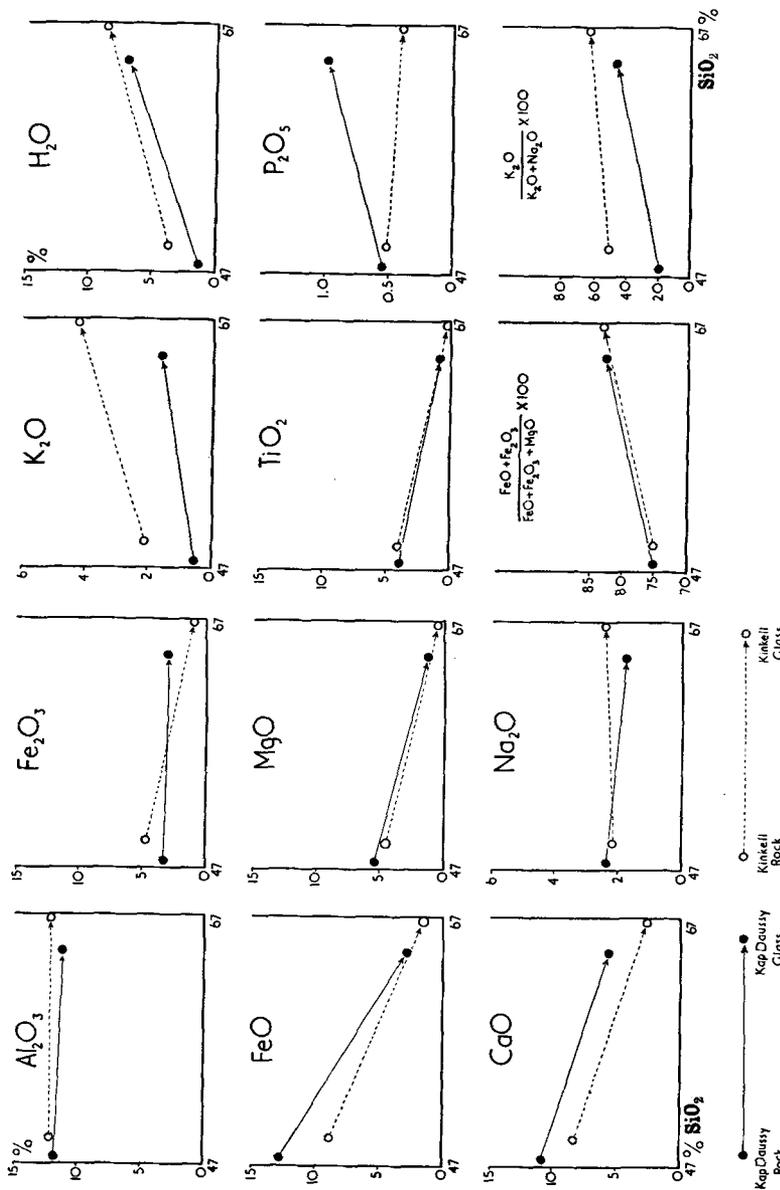


Fig. 2. Chemical composition of the Kap Daussy (Greenland) and Kinkell (Dumbartonshire) tholeites and of their residual glasses.

It is quite surprising, however, that for the majority of the oxides these tie-lines for the Greenland and Kinkell rocks are very nearly parallel, indicating a close correspondence between the parent magma and its late residuum. In most cases the increase or decrease of a particular oxide from rock to glass is much the same for a corresponding increase in silica. For example, the tie-lines for CaO and total FeO + Fe₂O₃ (iron oxides are only shown separately in fig. 2) are strikingly parallel, with the line for the Kap Daussy tholeiite well above that for the Kinkell rock. Similarly, the K₂O lines do not diverge widely, the Kinkell line being well above the other. In a general way it is seen that iron oxides, magnesia, lime, and titania decrease to roughly the same extent for a similar increase in silica in both instances considered, while potash and water increase in the same way. Alumina and soda remain essentially steady.

In his earlier description of the Kinkell tholeiite, Walker (1930) remarks that Fenner believed the low refractive indices of certain residual glasses to be due, partly at least, to relatively high concentrations of phosphates, borates, and silicofluorides, the iron having escaped with the volatiles. The analyses of both the Kinkell and Kap Daussy glasses show them to be 'acid'. The latter has not been analysed for boron, but a spectrographic examination of the Kinkell rock showed less than 1% B₂O₃, and Walker remarks (1930, p. 375) that it is extremely doubtful whether this would lower the refractive index of the glass. The amount of P₂O₅ in the Greenland glass, however, is nearly twice that in the parent rock. This is mainly due to tiny inclusions of apatite, but it is possible that there is still some phosphorus in solution in the glass. If this were in fact the case, it would tend to reduce the refractive index to a slight extent, since the specific refractivity of apatite (Tilley, 1922) is 0.201, slightly below the values given for most of the other normative minerals. The effect is probably negligible for the small amount of normative apatite which possibly remains occult in the glass.

Crystallization sequence of the Kap Daussy dike magma.

Although the known chemical composition of the residual glass from the Kap Daussy tholeiite provides tangible data for one point in the course of consolidation of the magma of this dike, it can, of course, give no direct information about the differentiation trend itself, only two points on the line being known. Comprehensive data are now available for the course of differentiation of several large masses of basaltic magma—for example, the Skaergaard intrusion (Wager and Deer, 1939)

TABLE I. Analyses of tholeiites and their residual glasses, with norms and modes.

| <i>Analyses.</i> — | | A. | I. | II. | B. | C. |
|--|------------------------|--------|-------------------|--------|-------|--------|
| SiO ₂ | ... | 47.35 | 47.42 | 64.03 | 49.10 | 66.80 |
| Al ₂ O ₃ | ... | 13.90 | 11.75 | 11.27 | 12.13 | 12.10 |
| Fe ₂ O ₃ | ... | 5.87 | 3.39 | 2.98 | 4.61 | 0.97 |
| FeO | ... | 8.96 | 12.79 | 2.81 | 8.92 | 1.50 |
| MgO | ... | 5.97 | 5.35 | 1.18 | 4.50 | 0.50 |
| CaO | ... | 10.65 | 10.83 | 5.57 | 3.20 | 2.62 |
| Na ₂ O | ... | 2.73 | 2.36 | 1.82 | 2.14 | 2.40 |
| K ₂ O | ... | 0.54 | 0.55 | 1.56 | 2.10 | 4.20 |
| H ₂ O + 110° | ... | 1.16 | 0.95 | 6.23 | 2.50 | 5.75 |
| H ₂ O - 110° | ... | 1.04 | 0.30 | 0.73 | 1.02 | 3.00 |
| TiO ₂ | ... | 1.75 | 3.98 | 0.79 | 4.02 | 0.18 |
| P ₂ O ₅ | ... | 0.24 | 0.54 | 0.98 | 0.51 | 0.39 |
| MnO | ... | 0.23 | 0.10 | 0.05 | 0.15 | n.d. |
| Others | ... | 0.55 | — | — | 0.03 | — |
| | | 100.94 | 100.31 | 100.00 | 99.93 | 100.41 |
| Sp. gr. | ... | 2.96 | 2.99 ₅ | 2.43 | — | 2.38 |
| <i>Ratios.</i> — | | | | | | |
| (FeO + Fe ₂ O ₃) | | | | | | |
| × 100 | | | 75.0 | 82.9 | 75.0 | 83.2 |
| FeO + Fe ₂ O ₃ + MgO | | | | | | |
| K ₂ O | | | | | | |
| × 100 | | ... | 18.9 | 46.1 | 49.5 | 63.6 |
| Na ₂ O + K ₂ O | | | | | | |
| <i>Norms.</i> — | | I. | II. | B. | C. | |
| qu | ... | 1.82 | 36.3 | 7.6 | 30.7 | |
| or | ... | 3.22 | 9.2 | 12.2 | 25.0 | |
| ab | ... | 19.96 | 15.4 | 17.8 | 20.4 | 55.4 |
| an | ... | 19.76 | 17.9 | 17.5 | 10.0 | |
| di | CaSiO ₃ ... | 12.68 | 1.4 | | 0.1 | |
| | MgSiO ₃ ... | 6.01 | 0.9 | 2.7 | 15.8 | 0.3 |
| | FeSiO ₃ ... | 6.50 | 0.4 | | 0.1 | |
| hy | MgSiO ₃ ... | 7.26 | 2.1 | | 1.2 | 2.5 |
| | FeSiO ₃ ... | 7.83 | 1.0 | 3.1 | 9.7 | 1.3 |
| mt | ... | 4.92 | 4.3 | | 6.7 | 1.4 |
| ilm | ... | 7.55 | 1.5 | | 7.6 | 0.5 |
| ap | ... | 1.28 | 2.3 | | 1.3 | 1.0 |
| Water | ... | 1.25 | 7.0 | | 3.6 | 8.7 |
| | | 100.04 | 99.7 | 99.8 | 100.5 | |
| <i>Modes</i> (% by volume).— | | I. | | B. | | |
| Plagioclase | ... | 38.2 | — | 28.3 | — | |
| Augite | ... | 31.7 | — | 22.4 | — | |
| Hypersthene | ... | — | — | 7.0 | — | |
| Olivine | ... | 3.3 | — | — | — | |
| Iron ores | ... | 6.5 | — | 10.8 | — | |
| Mesostasis | ... | 20.3 | — | 31.5 | — | |

A. Tholeiite of Salen type (Geol. Surv. No. 16808), dike, $\frac{1}{4}$ mile SSE. of Kintallen, Mull. Analyst, F. R. Ennos (quoted from Mull Memoir, Bailey, 1924, p. 17).

I. Olivine-tholeiite dike (E.G. 1123), Kap Daussy, east Greenland. Analyst, E. A. Vincent (new analysis).

II. Residual glass from olivine-tholeiite E.G. 1123. (Analysis IIa in table II corrected for presence of 2% feldspar and recalculated to 100.00%). Analyst, E. A. Vincent (new analysis).

B. Tholeiite dike of Upper Carboniferous age, Kinkell quarry, Kirkintilloch, Dumbartonshire. Analyst, J. Jakob (quoted from Walker, 1930, p. 368).

C. Residual glass from Kinkell tholeiite. Analyst, F. Herdsman (quoted from Walker, 1935, p. 150).

TABLE II. Analyses of residual glasses with comparisons.

| | IIa. | II. | IIb. | C. | D. | E. |
|---------------------------------------|--------|--------|--------|--------|-------|--------|
| SiO ₂ | 63.96 | 64.03 | 68.82 | 66.80 | 65 | 62.37 |
| Al ₂ O ₃ | 11.60 | 11.27 | 12.11 | 12.10 | 12 | 12.04 |
| Fe ₂ O ₃ | 2.93 | 2.98 | 3.20 | 0.97 | 6 | 1.87 |
| FeO | 2.76 | 2.81 | 3.02 | 1.50 | | 5.81 |
| MgO | 1.16 | 1.18 | 1.27 | 0.50 | 1.7 | 0.97 |
| CaO | 5.65 | 5.57 | 5.99 | 2.62 | 3 | 3.51 |
| Na ₂ O | 1.91 | 1.82 | 1.96 | 2.40 | 3.5 | 3.47 |
| K ₂ O | 1.55 | 1.56 | 1.68 | 4.20 | 3 | 2.34 |
| H ₂ O + 110° ... | 6.12 | 6.23 | — | 5.75 | — | 5.54 |
| H ₂ O - 110° ... | 0.72 | 0.73 | — | 3.00 | — | 0.44 |
| TiO ₂ | 0.78 | 0.79 | 0.85 | 0.18 | — | 1.06 |
| P ₂ O ₅ | 0.96 | 0.98 | 1.05 | 0.39 | — | 0.30 |
| MnO | 0.05 | 0.05 | 0.05 | n.d. | — | 0.24 |
| Others | — | — | — | — | — | 0.07 |
| | 100.15 | 100.00 | 100.00 | 100.41 | — | 100.03 |
| Sp. gr. | 2.43 | — | — | 2.38 | — | — |
| Refr. index | 1.516 | — | — | 1.495 | — | — |
| | F. | G. | H. | J. | K. | L. |
| SiO ₂ | 68.45 | 62.63 | 69.57 | 65.20 | 69.32 | 70.62 |
| Al ₂ O ₃ | 10.00 | 12.19 | 13.03 | 13.72 | 12.27 | 12.34 |
| Fe ₂ O ₃ | 5.71 | 2.98 | 0.98 | 3.63 | 0.06 | 2.25 |
| FeO | 2.59 | 2.89 | 3.59 | 3.72 | 6.81 | 3.17 |
| MgO | 3.26 | 1.49 | 1.06 | 1.01 | 4.05 | 3.61 |
| CaO | 6.20 | 4.84 | 1.56 | 2.79 | 3.72 | 2.99 |
| Na ₂ O | 1.98 | 2.12 | 4.57 | 5.22 | 0.77 | 1.68 |
| K ₂ O | 1.18 | 0.82 | 2.37 | 2.17 | 2.18 | 1.57 |
| H ₂ O + 110° ... | 0.62 | 4.11 | 2.04 | 1.27 | — | — |
| H ₂ O - 110° ... | 0.18 | 3.94 | | | 0.72 | — |
| TiO ₂ | 0.20 | 1.53 | 0.65 | 0.39 | — | — |
| P ₂ O ₅ | 0.25 | 0.35 | 0.47 | 0.38 | — | — |
| MnO | 0.05 | — | — | n.d. | — | — |
| Others | — | — | 0.89 | — | — | — |
| | 100.67 | 99.89 | 100.78 | 100.22 | — | — |
| Sp. gr. | — | — | — | — | 2.498 | 2.442 |
| Refr. index | — | — | — | — | 1.526 | 1.51 |

IIa. Glass concentrate separated from tholeiite (E.G. 1123), Kap Daussy. Analyst, E. A. Vincent (new analysis).
 II. Analysis IIa, corrected for 2% plagioclase contamination.
 IIb. Analysis IIa, calculated water free.
 C. Residual glass from Kinkell tholeiite, Dumbartonshire (Walker, 1935).
 D. Normal Mull magma series for 65% SiO₂.
 E. Inninmorite-pitchstone, ½ mile SW. of Pennyghael, Mull (Anderson and Radley, 1915).
 F. Granite-gneiss, Fredericksburg, Virginia (Washington's Tables, p. 332).
 G. Dacite-pitchstone, Morateno, Madagascar (Washington's Tables, p. 332).
 H. Segregation vein in quartz-dolerite, Fifeshire (Day, 1928, quoted in Walker, 1935).
 J. Felsitic vein in Whin Sill, Alnwick Moor, Northumberland (Tomkeieff, 1929).
 K. 'Tektite', Martapoera, Borneo (quoted in Spencer, 1939).
 L. 'Tektite', Kalisso, Java (quoted in Spencer, 1939).

and the Karroo dolerites (Walker and Poldervaart, 1949), among others, and less definite data from Mull (Bailey, 1924)—but positive data of a similar kind for various stages during the crystallization of a small body of magma in, say, a dike or a sill, are still needed. We cannot, of course, hope to be able to follow the process of crystallization-differentiation at all easily in these small intrusions, but further chemical data even on their late stage residua, where these can be separated, would be very valuable. It is worth while, however, to see how this one residual glass compares with one or two of the well-known differentiation series of rocks commonly believed to be derived from basaltic magmas.

First, there is the normal Mull magma series, regarded by the authors of the Mull Memoir (Bailey, 1924) as a series resulting from the crystallization-differentiation of a parent basaltic magma. The Kap Daussy tholeiite analysis (analysis I, table I) fits fairly well on the variation diagram (fig. 2 in the Mull Memoir) for the normal Mull magma series at 47 % SiO_2 . Its glassy residuum, however, cannot be made to fit into this same series at 64 % SiO_2 . The discrepancies—high lime, low alkalis—are evident when the glass analysis is compared with columns D and E in table II. The Mull variation curves are supported by many analyses, and it is evident that the Kap Daussy glass simply does not belong to a comparable differentiation series: it does not show sufficient enrichment in alkalis.

An admirable summary of the trends of differentiation in basaltic magmas has recently been given by Walker and Poldervaart (1949, pp. 650–665) who believe, with Wager and Deer, that the normal course of differentiation leads to iron enrichment in the early and middle stages, and enrichment in silica and alkalis towards the end. In contrast to such a series (exemplified by the Skaergaard magma) is the ordinary calc-alkaline series, represented by Daly's average basalt, andesite, dacite, and rhyolite, and by the rocks of the Garabal Hill–Glen Fyne complex (Nockolds, 1941). Wager and Deer (1939) believe this latter calc-alkaline series to be in the main derived from mixing acid and basic materials; while Nockolds considers the Garabal Hill series to be an example of straight crystallization-differentiation. Walker and Poldervaart (1949, p. 661) 'consider it likely that the calc-alkaline suite may be produced by fractionation of basalt magma, though they do not exclude the possibility of assimilation of sialic material, followed by crystallization-differentiation of the hybrid magma'.

To illustrate these contrasted differentiation series, Wager and Deer made use of a triangular diagram to plot FeO, MgO, and $K_2O + Na_2O$. This method is adopted by Walker and Poldervaart, who give a series of such diagrams to illustrate a number of magmatic series.

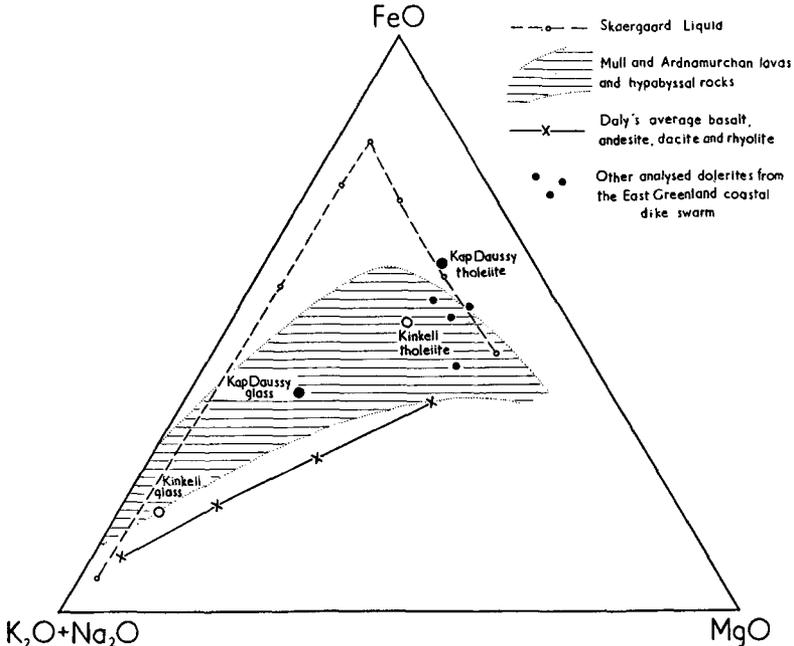


FIG. 3. Relation of the Kap Daussy and Kinkell tholeiites and residual glasses to the differentiation trends of the Skaergaard (Greenland) and calc-alkaline series.

If the Kinkell tholeiite and its glass and the Kap Daussy tholeiite and its glass are plotted on such a diagram (fig. 3), it is seen that the former glass lies close both to the Skaergaard trend and to the calc-alkaline trend where these converge towards the $(K_2O + Na_2O)$ corner of the triangle, though its parent rock is not particularly close to either trend. The Kap Daussy tholeiite itself falls in this diagram practically on the line for the Skaergaard series, and the four other dolerites from the east Greenland coastal dike swarm so far analysed are also fairly close to this line. Most of the Mull and Ardnamurchan lavas and basic hypabyssal rocks fall slightly nearer to the $(K_2O + Na_2O)$ corner of the triangle than do the Greenland rocks.

The residual glass from the Kap Daussy tholeiite, however, occupies

a curious position midway between the two trends, and although on this diagram it lies inside the field occupied by the Mull series, it is rather isolated there, its nearest neighbours being two inninmorite-pitchstones and two leidleitites. The FeO-MgO-(K₂O+Na₂O) diagram, satisfactory as it is for showing the main differentiation trends, does not suit the Kap Daussy residual glass particularly well, as it takes no account of percentages of silica or of lime.

It has been found that the ratios

$$(\text{FeO} + \text{Fe}_2\text{O}_3)/(\text{FeO} + \text{Fe}_2\text{O}_3 + \text{MgO}) \times 100 \quad \text{and} \quad \text{K}_2\text{O}/(\text{K}_2\text{O} + \text{Na}_2\text{O}) \times 100$$

provide useful criteria of differentiation in series of rocks derived from basaltic magma (cf. Wager and Deer, 1939, pp. 299-305; Walker and Poldervaart, 1949, p. 652), and are certainly of more fundamental significance than silica percentage. The 'iron ratio' is useful for the earlier stages and the 'alkali ratio' for the later ones. These ratios have been calculated for the rocks and glasses considered here, and are plotted against silica percentages in fig. 2. Once again the tie-lines are nearly parallel. Using the ratio $(\text{FeO} + \text{Fe}_2\text{O}_3)/(\text{FeO} + \text{Fe}_2\text{O}_3 + \text{MgO}) \times 100$ as a criterion, the two glasses seem to have differentiated from their parent rock magmas to much the same extent, while the Kap Daussy glass shows a rather more marked concentration of potash in the total alkalis. Referring to fig. 2, it is seen that the various diagrams could equally well have been plotted with the ratio

$$(\text{FeO} + \text{Fe}_2\text{O}_3)/(\text{FeO} + \text{Fe}_2\text{O}_3 + \text{MgO}) \times 100$$

as the abscissa (instead of percentage SiO₂), and the parallel arrangements of the tie-lines would still be evident.

Whether silica percentage or iron ratio is used as a measure of differentiation, then, it seems that the course of crystallization in the Kinkell and Kap Daussy dike magmas may have been rather similar, the end-product represented by the residual glass depending upon this course as well as upon the composition of the parent magma. In this connexion, the diagram for P₂O₅ in fig. 2 is of some interest. The Kap Daussy glass with its inclusions of apatite, which together represent the residual magmatic solution, is enriched in phosphorus, while the Kinkell glass contains less phosphorus than its parent rock. In the Skaergaard magma it was found that the P₂O₅ content increased steadily through the differentiation series until the later stages, when it fell suddenly and rapidly. A similar effect may be taking place in the Kap Daussy dike magma, this particular residual solution representing a stage at

which the concentration of phosphorus was around the maximum. Had the residuum represented, say, only about 10 % of the magma, it may well have been quite poor in P_2O_5 , as is the Kinkell glass.

This point lends some support to the view that if the Kap Daussy glass represented a smaller proportion of its parent magma, it might approach the more ordinary composition of the Kinkell glass somewhat more closely, although the characters inherited from the parent magma—high iron oxides and lime, and low potash—persist to a relatively late stage in the present glass, and it seems unlikely that an even later stage residuum would be really close to the Kinkell glass in composition.

There is insufficient evidence to show whether or not the course of differentiation of the Kap Daussy dike magma has followed the characteristic iron-enrichment trend shown by the Skaergaard magma and the Karroo dolerites, and it does not appear either to have followed closely the trend of the normal Mull magma series. It appears to have followed a rather unusual course which did not lead to a residual magma of granitic composition. Further separation and analysis of similar residual glasses is much needed in order to try to establish the trends of the later stages of crystallization-differentiation in small intrusions of the kind considered here.

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