# THE UNDERGROUND PHASE OF VOLCANIC ACTIVITY

By

FREDERICK WALKER

*University of St. Andrews, at Dundee*

**The R. M. Johnstone Memorial Lecture**
**August, 1957**


## ABSTRACT

A survey is made of the hypabyssal activity associated with kratogenic outpourings of plateau basalt. It is shown that sheet and sill injection have volumes of the same order as that of the lava phase and far greater than that of the dyke phase. The form of lateral injection and its position in the time sequence of vulcanicity are discussed and also the possibility of hydrostatic control acting as a governing factor. Consideration is given to the quantitative aspect of contact phenomena, in particular of metasomatism. The relationship between the olivine basalt and tholeiitic magma-types is touched on briefly.


## INTRODUCTION

Igneous activity is probably the most important of all natural phenomena. Not only is it fundamental in the evolution of the earth's crust, but its surface manifestation, volcanic extrusion is both spectacular and terrifying. Yet volcanic outbursts are accompanied by underground phenomena of even vaster scope. These cannot be seen in action, but erosion, working through millions of years, has laid bare their secrets and has shown them to provide important clues to that most difficult problem, the diversification of igneous rocks. In what follows I will attempt to summarise some of the evidence to be found on this question in the less deep-seated of igneous injections.

## GRANITE AND BASALT

It is many years since Daly called attention to the dominance of basalt amongst volcanic rocks and of granite amongst deep-seated intrusions. If these two rock names are used in their broadest sense to include pyroxene andesite, oceanite and limburgite in the first case and granodiorite in the second, their position is even more outstanding. But, as Kennedy has emphasised (in Kennedy and Anderson, 1938, pp. 27-33), there are profound differences other than that of chemical composition between these fundamental rock-types. Basalt with its underground equivalents dolerite, gabbro and norite, is of volcanic association connected with extrusive outbursts during which basic magma made its way swiftiy to the surface. Granite, by contrast, is of plutonic habit. It too may have its surface equivalents but these are rare and insignificant. The vast majority of granite batholiths had no surface connection, being formed at depths measurable in miles rather than feet. Granite formation seems to have been a slow process, even by geological standards, involving wide-spread soaking and impregnation with metasomatic transfer of enormous quantities of material. Only the relatively scarce granites of volcanic association show the clear-cut margins and chilling phenomena characteristic of the basalt clan.

It is this basalt clan that concerns us here. The granitic phase of crustal injection is still too problematical for accurate assessment and in any case has been fully discussed in recent years, notably by Read (1957). Basaltic rocks, on the other hand, have may properties which are measurable quantitatively and throw light on the problems of differentiation.

### Dolerites as Subjects for Study

Recent work on the basalt clan may be grouped under three headings:—

(1) Optical and chemical surveys of deep-seated and highly-differentiated intrusions such as the Skaergaard, Stillwater and Bushveld. In spite of their great size, these belong to the volcanic associations of Kennedy.

(2) Attemps to arrive at general principles by collation of chemical and optical data.

(3) Studies of the differentiation of individual hypabyssal intrusions or of lava series.

I will now attempt to show why investigation of hypabyssal intrusions, especially of flat-lying sheets and sills is of particular importance, and to make a broad quantitative survey of this type of igneous activity. My reasons for concentrating on flat-lying intrusions are these:—

(*a*) Their aggregate volume greatly exceeds that of dykes.

(*b*) The majority have been emplaced by a single impulse and even in cases of composite or multiple intrusion, the sequence is relatively simple. This is in marked contrast to the great layered intrusions of lower levels where the problems of differentiation are complicated by strong convection.

(*c*) All flat-lying bodies possess a definite floor and roof against which constituents rising or settling during the cooling process tend to accumulate . In basalt lavas roof foundering and turbulent flow over uneven surfaces may render investigation more difficult. Differentiated dykes may also possess roof and floor but such cases are rare and often poorly exposed.

(*d*) The limited thickness of differentiated sheets and sills makes for rapid investigation. In many cases exposures are excellent and in a few complete bore-cores are available. In lavas these advantages are off-set by marginal vesiculation and decomposition.

(*e*) Most sheets or sills have well-marked chilled margins which yield accurate information as to the composition of the magma at the time of emplacement. These are generally lacking in lavas.

(*f*) Rheomorphic, anatectic and metasomatic phenomena, as well as assimilation, are on a more limited scale than in plutonic masses which leads to relatively easy detection and investigation.

(*g*) Hypabyssal intrusions show a transition between plutonic and volcanic conditions and are therefore useful in indicating the limits of stability of the constituent mineral series under varying physical conditions. This applies with special force to the pyroxenes and plagioclase felspars.

It will thus be seen that the investigation of flat-lying dolerite intrusions is likely to be particularly rewarding and that the facilities they afford are shared by dykes to a much lesser degree and still less by lavas. Let us see now how these sheets and sills bulk in the earth's crust, whether greater or less than basaltic lavas, and how they compare with the great layered intrusions. In this survey the primary and parental nature of basic magma is a vital premise.

### Volume Comparison between Basalt and Dolerite

Basic rock in the form of basalt or dolerite is dominant in all the great lava plateaus of the world and in their associated hypabyssal intrusives. It seems, indeed, that the rapid ascent of molten sima during periods of crustal tension is the distinguishing characteristic of this type of vulcanicity. But when one attempts to estimate the relative bulk of the extrusive and hypabyssal phases difficulties are at once encountered.

In the case of the lavas there can be no evidence, except in recent outbursts, of the proportion removed by erosion. An extreme example is seen in Tasmania where the post-Triassic dolerites have no equivalent extrusive phase exposed. We cannot here be sure as to whether any lavas of this age actually existed. Only in lava series interbedded with sediments can there be any certainty as to the original thickness.

Another difficulty is in tracing the lateral extent of eroded basalt plateaus. Since basalt breaks down quickly during transport it is unlikely to be found in conglomerates. Some cases, however, may reveal slumped masses of basalt lavas which have now been completely stripped from the surface. An excellent example of this is found in Arran (Tyrrell, 1928, 181), and another still more striking in the Karroo near Prieska (du Toit, 1954, 417). In the latter case the presence of slumped Stormberg lavas in kimberlite pipes demonstrates that the basaltic flows of the Basutoland plateau extended westward for at least 300 miles beyond their margin today.

The difficulty of estimating the bulk of magma in a hypabyssal assemblage is also formidable. The volume of the dyke phase is relatively small and we may, in the meantime, confine our attention to the more concordant and flat-lying intrusions. There seems to be a definite tendency for basic magma to spread laterally at well-marked geological horizons, possibly through hydrostatic control, and there are seldom more than three or four levels of such spread. This is well seen along The Great Escarpment of South Africa—in particular in the deep valleys of the Transkei. The same is doubtless true of the Tasmanian dolerites but dense bush tends to mark the lower outcrops. Exposures are also poor in the Palisadan province but here as in Tasmania, drilling has yielded compensating information.

In the Karroo and Palisadan provinces the extrusive and intrusive phases seem to have volumes of the same order. In the focal region of the Karroo activity the total thickness of the lavas probably exceeded that of the sills, but in outlying areas the aggregate thickness of sills and sheets was probably the greater amounting to over 3,000 feet in the Stormberg and Kokstad districts. In the Palisadan province the total thickness of the lavas reaches a maximum of 900 feet against at least 2,000 feet for the flat-lying intrusions. In addition, there can be little doubt that the sills and sheets had the greater lateral extent.

The sill phase of the Lower Carboniferous activity of Central Scotland is probably less in volume than the plateau lavas but again the bulk of both is of the same order. One of the chief difficulties in making these estimates is in the determination of the lateral extent of the sills and sheets, but the general indication is that in a given terrain the flat-lying intrusions thin out more gradually and extend further than the equivalent lava series. It is at any rate clear that the volume of hypabyssal basic rock accompanying the great plateal eruptions is in no way dwarfed by them and in some cases is actually greater.

### The Relationship of Deep-seated, Layered Complexes to Dolerite and Basalt

The layered lopoliths and kindred intrusions of more deep-seated habit are sometimes of such dimensions as to approach an entire sill suite or lava plateau in bulk. Thus the Bushveld Igneous Complex of the Transvaal with a probable volume of over 250,000 cubic miles greatly exceeds that of the associated suite of diabase sills or the volcanic series which were its harbingers. This, however, is an extreme case and the lavas and minor intrusions of the Bushveld are not comparable in bulk to the Stormberg volcanics or the associated Karroo dolerites.

Other lopolithic masses of similar dimensions are known, e.g., that of Duluth, but they are not common and it is doubtful whether their world volume approaches that of the great lava plateaus with their associated minor intrusions. It may, nevertheless, be noted that the hypabyssal bodies sometimes contain numerous xenoliths of peridotite and other rocks formed under deep-seated conditions so that the presence underground of major plutonic intrusions may be inferred even if they are not exposed. Such phenomena are frequent in the hypabyssal intrusions associated with the Carboniferous volcanics of Central Scotland.

### The Volume of Dyke Swarms

Lastly there are the associated dyke swarms to be considered. Each major lava plateau has its dykes which may form the actual feeders of the flows, but sometimes represent a later and final ascent of magma under conditions of crustal tension. The dyke swarms bulk in general far less than the lavas and flat-lying intrusions. In the Karroo, Palisadan and Tasmanian provinces (Trias-Jura) and the Central Valley province of Scotland (Carboniferous) this is quite obvious from the examination of the relevant geological maps. The British Tertiary province, however, provides a case where not only is dyke intrusion much more abundant but where quantitative data are available. The most spectacular development of dykes is at the margins of the great plutonic centres, notably Mull and Arran, where admirably exposed shore-sections are available. Here the dyke swarms have aggregate thicknesses of 2,504 and 6,050 feet respectively, figures which match those of even the greatest lava plateaus or their sill suites. But the height and length of a dyke are by no means comparable with the equivalent measurements of an important sill, that is the lateral spread which may cover over 4,000 square miles. Furthermore, the dyke swarms of Mull and Arran fall off rapidly in thickness away from the plutonic foci (Richey, 1939, 424).

There remain the cone-sheet systems of the British Tertiary ring structures. No details of their aggregate thickness are available but around the plutonic centres of Mull and Ardnamurchan, where they find their strongest development, it must amount to several thousand feet. Their vertical and lateral extent is, however, strictly limited so that their volume will be much less than that of a dyke-swarm.

The main conclusion to be drawn from this brief survey is that the sill phase matches in bulk, if no more, the extrusive and the lopolithic and may well exceed them as dyke swarms and cone-sheet systems have aggregate volumes of a distinctly low order.

### The Origin and Relationship of the Sill and Lava Phases

Neglecting for the moment dyke swarms and deep-seated layered intrusions, we may now examine the structural relationships of the sill and lava phases of flood-basalt episodes. It is of particular importance to determine the sequence of activity and how this may be modified by the structure of the invaded rocks.

Whatever local variations in structure there may have been during these eruptions it is at least certain that they are all associated with periods of marked crustal tension. Only this could permit the rapid ascent through fissures of vast volumes of basaltic magma derived from reservoirs (presumably stratiform) of fused sima. Where the rocks underlying the great lava plateaus have been trenched deeply by erosion the habit of the flat-lying intrusions is seen to be controlled by the structure of the rocks traversed, though the detailed mechanism and the sequence of events remain uncertain. Consideration of a few carefully studied provinces of which I have personal knowledge will illustrate this.

*Karroo Dolerites and Stormberg Lavas.*

In the Karroo province of South Africa the ascent of basic magma through the Basement Complex was by narrow dyke fissures. These continued upwards into the flat-lying sediments of the Karroo System in which the magma developed a tendency to spread laterally. At low horizons in the System the spread was largely concordant but at higher levels cross-cutting sheets are found which become less common in the Stormberg Series and absent from the lavas themselves. The concordant intrusions tend to follow bedding planes between siltstone and pelitic layers, especially above the massive well-jointed siltstones which are prominent in the Beaufort Series.

The cross-cutting sheets have been termed " conical sheets " by Lombaard (1953, 181-186) and compared to true cone-sheets. They are considered by him to have stemmed from convex irregularities or cupolas on the roofs of concordant sills. From these they made their way upwards until in the Stormberg Series they developed sufficient gas pressure to break through to the surface and form numerous ash vents of central type, sometimes invaded by dolerite or basalt. These vents are abundant in the Cave Sandstone north of 29° 30′ and their relationship to the conical sheets is complementary. Freezing of the magma from above downwards then sealed off the early channels and it was left to a set of younger dykes to ascend and pour out at the surface as the Stromberg Lavas. There is little doubt that these volcanics arose from fissure eruptions, for the dyke feeders are seen to penetrate to high levels in the lava plateau. Lombaard appears to envisage the following sequence of events:—

(1) Ascent of early dyke-suite into Karroo System.
(2) Lateral spread of concordant sills in lower part of System.
(3) Ascent of conical sheets from cupolas on roofs of sills.
(4) Increasing gas pressure at higher levels causes conical sheets to break through to surface and form ash-lava vents of central type.
(5) Freezing of magma from vents downwards seals off further ascent of magma.
(6) Renewed tension gives rise to later dyke swarms which reach surface and build up lava plateau.

Du Toit, on the other hand (1954, 567-568) proposed a different sequence:—

(*a*) Breaking through of diatremes and ash-lava vents of central type in Cave Sandstone time.

(*b*) Fissure eruptions build up lava plateau.

(*c*) Impenetrability of thick lava cake leads to lateral spread of magma underground to form sill and sheet phase.

(*d*) Renewed tension results in main dyke phase which penetrates lavas.

Scholtz (1937, 202, 203) agrees with du Toit in considering that early extrusion produced an impenetrable lava cake causing the magma to spread laterally in the underlying sediments.

Here, then, in a province with fully developed and admirably exposed extrusive and hypabyssal phases opinions differ as to the sequence of events. We may notice, however, that Lombaard's conception of conical sheets differs from the type examples by comprising a single cone-shaped injection instead of a concentric series with increasing dip towards the centre.

*The Dolerite Dykes of the Cape Peninsula.*

In the Cape Peninsula and its immediate vicinity there is developed a series of tholeiitic dykes which are probably of Karroo age since they cut Siluro-Devonian strata of the Table Mountain Series. The behaviour of the magma is different here. It penetrates the Precambrian granite and associated metamorphic rocks by means of short narrow dyke fissures. These traverse the basal shales and flagstones of the Table Mountain Series but end abruptly without any tendency to spread laterally when the first massive quartzite is reached. The Table Mountain sediments, though lying relatively undisturbed between two tighly folded orogenic zones of the Cape Foldings, are nevertheless closely cemented and brittle with widely spaced joints so that magma would find no easily followed horizontals channels as in the Karroo sediments.

*Palisadan Dolerites and Lavas.*

The basic rocks of the Palisadan province are less perfectly exposed than those of the Karroo but have been studied as fully. Yet they provide no further clues as to the sequence of eruption. Recent work by Hotz (1952) on the Pennsylvanian sheets, aided by extensive drilling, has, however, thrown light on the form of the sheets. Few of them are strictly concordant, the majority having a marked inward dip producing annular outcrops very similar to those of the conical sheets in the Karroo. Drilling has shown that they have a platter-like shape with horizontal floors and one therefore wonders whether the Karroo sheets may not also have this form. It must be noted, however, that unlike those of the Karroo, the Palisadan sheets were injected into Triassic strata which had been already gently flexed and faulted, and that though the inclined sides of the body may be conformable, the horizontal floors are transgressive. Furthermore, the extrusives of the province were relatively unimportant. The magma traversed pre-Triassic formations by means of dyke fissures.

Hotz makes a comparison with the Karroo sheets but comes to no definite conclusions as to the mode of origin or the position in the eruptive sequence of the Pennsylvanian sheets.

*Tasmanian Dolerites.*

In the Tasmanian province which is penecontemporaneous with the Palisadan and the Karroo, the volcanic phase is entirely absent from present exposures and may never have existed. As in the Karroo, the Permo-Triassic sediments are largely undisturbed and flat-lying. In the following brief account I have been aided by stimulating discussion with Professor S. W. Carey and Mr. A. Spry. The latter has added to my indebtedness by providing a written summary of his views, which I quote below:—

> "Sedimentation (total of about 4-5,000 feet of Permo-Triassic) on a folded basement continued up to the time of intrusion. The magma must have risen through major fractures in the basement but then reached materials which were quite different in their physical properties. This is similar to the examples of the Cape dykes where intrusion passes up through granite then ceases in overlying sediments. It seems that crustal tension caused fractures in the brittle granite but is relieved by interangular movement or jointing in the overlying sediments. In Tasmania I think that the dolerite magma rose through quite large openings in the basement (dykes, ring-dykes or cone-sheets), but when it reached the base of the sediments it met materials which were soft, semi-consolidated and *lighter* than itself. The magma found it easier to intrude along the strong bedding planes and to lift its light roof than to burst through to the surface because major vertical fractures would be sparse. One might expect a thickening of the body near the source to give a laccolithic habit but this does not seem to be so here. It looks more like the synchronous intrusion of magma from a whole series of sources with the coalescing of the magma to give a very large sheet which runs horizontally and steps up and down. If liberation of the magma had continued then one might have expected surface volcanism to follow intrusion because the sediments would have been rendered brittle by the abundant dolerite.
>
> "It seems to depend on local conditions which happens first because the magma will travel along the easiest path. It is likely that if the magma is liberated at the surface by a vent and then becomes solid later, magma will be encouraged to move sideways and form intrusions. One must evaluate the relative importance of the strong pressure gradient tending to burst the magma through to the surface against the bedding plane and joint weaknesses tending to encourage intrusion. The relative densities of the magma and the country rocks are, of course, very important as will also be the regional tectonics of the area."

In Tasmania Professor Carey and Mr. Spry take the view that lateral spread in partly-consolidated sediments proved easier than a break through to the surface and that extrusion, if it ever took place, came after the phase of sill injection. Mr. Spry's contention that sill injection renders the sediments more brittle will be discussed at a later stage.

*Permo-Carboniferous Province of Central Scotland.*

Having now dealt with three tholeiitic provinces, we now turn our attention to one which is dominantly alkaline olivine basalt. Though small, it has been mapped in greater detail and more carefully studied than any other. The associated sediments range through the whole of the Carboniferous System into the Lower Permian and are flexed and faulted without any trace of metamorphism. A very complete and thoroughly documented account of the eruptive sequence in time and place has been given by MacGregor (1948).

In this province, sill injection and extrusion of alkaline olivine basalt magma are of equal importance. Dyke injection is localised and of quite minor character except for a strongly developed system of E.-W. tholeiitic dykes which came as an unheralded interruption at the close of the Carboniferous. MacGregor, following Kennedy and Anderson (1938), attempts to account for the variation in the eruptive types by an hypothesis of crustal layering with fusion at different levels at different periods. Other mechanisms have been proposed by Daly (1933, 391-392) and by Tomkeieff (1937).

In the eastern portion of the Midland Valley there is definite evidence that extrusion of lavas preceded sill injection. The volcanics occur in the Calciferous Sandstone Series down to the very base but are not found in the succeeding Carboniferous Limestone Series. On the other hand, the sills, besides spreading at all levels in the Calciferous Sandstone Series, occur abundantly in the Carboniferous Limestone Series, though conspicuously absent from the Millstone Grit and Coal Measures of the Midlothian and East Fife coal basins. There is evidence that some of them are of Calciferous Sandstone age, for examples in that series have their upper contacts veined with unconsolidated sediments of that facies. The Armorican stress system prevailed throughout this period and the sills are concordant with step-like transgressions as in Tasmania.

Both extrusive and intrusive activity persisted longer in the west, but before the close of the Carboniferous the magma channels became sealed off. The next episode was the injection under the succeeding Borcovician stress system (Anderson, 1951, p. 43) of a great series of tholeiitic dykes and sills. These were followed by a recurrence of alkaline olivine basalt lavas and intrusions in early Permian time, the relationship between extrusive and intrusive bodies being similar to that prevailaing in the Lower Carboniferous though with certain modifications, e.g., a Permian agglomerate vent is visibly connected with a 30-feet monchiquite dyke in Ayrshire.

We may now apply Mr. Spry's suggestion that sill injection by hardening the invaded sediments and rendering them more brittle modified the nature of subsequent eruptive episodes. This does not appear to have been the case in the Midland Valley. The great alkali dolerite sill system of the Carboniferous and the later quartz dolerite dykes and sills have not been able to alter the contact sediments significantly or to alter the eruptive time sequence in subsequent Permian outbursts. These resemble in all major points the Lower Carboniferous activity and there is good evidence that in this province that the magma broke through to the surface without spreading laterally in the contact sediments consisting largely of interbedded sandstone and shale which would have provided easy passages for conformable injection. Conditions of crustal tension must have prevailed for this to happen and the paucity of dykes is rather surprising. It is clear, however, that both lava and sill phases were fed through mapor orifices and not narrow dyke fissures.

*Scottish Tertiary Province.*

The Scottish portion of the vast Brito-Icelandic province has received the same large-scale mapping and detailed study, but the associated sediments are flat-lying as in the Karroo and Tasmania and the vulcanicity is characterised by a spectacular development of ring-structure (Richey, 1932). Another feature of the province is the appearance at an early stage of both tholeiitic and olivine basalt lavas.

The evidence in Skye favours the view that lavas fed through dyke fissures preceded the main phase of sill injection (the Great Sill Group), the plutonic rocks of the Coolin centre intervening. These sills consist of alkaline olivine dolerite with picritic differentiates and are considered by Harker (1904, Chapter XIV) to occur abundantly in the plateau lavas as well as in the underlying sediments. Later work by Kennedy (1931, 166) and others has shown that in some cases they are the compact centres of lava flows but there is no doubt that sills belonging to the Great Group do occur in the plateau lavas. The majority of these sills, however, are intruded into the underlying Mesozoic formations in which their aggregate volume is very great. They are extremely concordant, on the whole, but may show step-like transgressions.

The focus of the Great Sill Group must lie to the north of Skye for the sills increase in aggregate thickness in that direction. There is not the same development of sills in other Tertiary centres except in South Arran where four thick crinanite sills are injected into the New Red Sandstone. They are themselves cut by later dyke swarms related to the plutonic centres, but there are no lavas to date them more precisely.

## General Observations

Of the five provinces discussed above, two show definite evidence that lavas preceded sill injection (Scottish Carbo-Permian and Tertiary). Two leave the matter in doubt (Karroo and Palisadan), while the remaining Tasmanian province has no visible extrusive phase (due, in the opinion of local geologists, to a tendency to spread laterally along bedding planes rather than to wedge through to the surface). All five provinces are in kratogenic regions where the eruptive episodes occurred under conditions of marked crustal tension, but, whereas dyke intrusion is conspicuous in the Scottish Tertiary and Karroo and moderate in the Palisidan province, it is relatively scarce in the Scottish Carbo-Permian and Tasmanian provinces where the magma was afforded upward passage through major orifices such is pipes and elongated bosses.

Amid this conflicting evidence it seems clear that the sill phase which we are now considering is developed regardless of the form of the vertical feeders. Furthermore, in the two most closely studied provinces where large scale mapping (6 inches = 1 mile) has been carried out, the sill phase succeeds the lavas which broke through to the surface without lateral spread.

Mr. Spry suggests that magma may find it easier to lift its roof and spread conformably in partly consolidated sediments than to wedge its way to the surface, but neither in Tasmania nor in the Karroo has convincing evidence been advanced. His further suggestion that the sediments may be rendered brittle by dolerite invasion, and so provide easier vertical passage for lava feeders, seems very doubtful. Even thick sills only affect the contact sediments for a few feet and the invaded strata as a whole suffer no significant modification.

On the other hand, the power of massive formations with widely spaced joints and little pore-space to halt the ascent of magma, is unquestionable in the case of the Cape Peninsula dykes which terminate below the first massive quartzite encountered. To sum up, it seems that rapid and direct ascent of basic magma to the surface initiates igneous activity in at least same kratogenic regions and that the sill phase followed, either as a result of hydrostatic control or the mechanical impenetrability of a thick cake of lava. No positive evidence is available that magma found it easier to spread conformably by lifting its roof than to break through to the surface, though such a process is clearly conceivable. The main horizon of sill injection may be quite restricted, which would indicate some form of hydrostatic control or may have an extended vertical range as in the Scottish Carboniferous.

### Diversification of Dykes and Flat-lying Intrusions

In distinguishing between volcanic and plutonic associations, Kennedy (in Kennedy and Anderson, 1938, 30-31), in common with other petrologists, has emphasised the importance of crystallisation differentiation in the former. This finds confirmation in every kratogenic province, but it will be seen that the differentiation trend in dykes differs from that in flat-lying intrusions. Dealing with the Tasmanian dolerites, Edwards (1942) has adduced ample petrological and chemical evidence to show that broad dykes may be regarded as open chambers, whereas flat-lying intrusions are closed.

*Crystallisation Differentiation in Dykes.*

The narrow dykes of great swarms are characteristically free from differentiation phenomena in place. Composite and multiple dykes are abundant, but each member thereof tends to be uniform in itself.

The case is very different in broad dykes or elongated bosses, the central portions of which were slowly cooled. Here the early formed mafic minerals (magnesian pyroxenes and olivine) tend to settle by gravity, once ascent of magma has ceased, to lower levels at which they are lost to observation. The result is a transition from chilled margins representing the composition of the magma at the time of emplacement to a centre impoverished in dark minerals. Gunning's Sugar Loaf (Edwards, 1942, 474-477) provides an almost perfect example of this process. The margins have compositions showing excellent agreement with the average for undifferentiated Tasmanian dolerite but a traverse to the centre exhibits a gradational change to felspar-rich pyroxene-poor varieties. The centre has the composition of an alkali-poor andesite very different from the iron-rich differentiates found in the upper portions of intrusions with roof and floor.

Such a mode of differentiation can only take place in really broad dykes or elongated bosses with parallel walls. If the dyke is floored at levels exposed by erosion, as in the case of Elephant's Head in South Africal (Poldevaart, 1944), the settling minerals will accumulate on the floor to form ultramafic types such as picrite or pyroxenite. The same result might, however, be brought about by a constriction in the passage and this is possibly the case in the Glen More ring dyke of Mull (Bailey and Thomas, 1924, Koomans and Kuenen, 1938). Even narrow dykes may show the results of differentiation, though not in place. Bowen (1928, 149-159) has described how the peridotite dykes of the Coolins in Skye have margins of olivine basalt representing the original magma which warmed up the passage and permitted the ultramafic accumulate to ascend. These, however, are in the nature of composite dykes, though the internal contacts may be transitional.

*Differentiation of Flat-lying Intrusions with Roof and Floor.*

The differentiation of sheets is in every way more diverse and important than that of open dyke chambers. There are two main reasons for this: first, because the roof and floor limit the rising and settling of crystals in the intrusion so that crystal accumulations become clearly visible in eroded examples; second, because the average thickness of a sheet tends to be greater than the average breadth of a dyke so that cooling is slower in sheets and gravitational differentiation more likely to occur, the more so because sill magma after injection is static, whereas a feeder dyke may be an open channel liable to many subsequent pulsations. Furthermore, as I have already emphasised, differentiated sheets may exhibit interesting transitional phenomena. In addition to the features of sills set forth earlier, the following may be noted:—

(*a*) By study of sills and sheets the critical dimensions at which significant crystallisation differentiation takes place may be determined and will be found to differ markedly in tholeiitic and olivine basalt provinces. Quite strong differentiation in place may occur in olivine dolerite sheets (in particular, teschenitic examples) under 100 feet thick, whereas a differentiated sheet of quartz dolerite or tholeiite is very rare.

(*b*) In tholeiitic sheets inversion from pigeonite to orthopyroxene is common and provides accurate estimates of the temperature of intrusion, e.g., slightly over 1100° C. in the Palisadan and Karroo provinces (Hess, 1956, 446).

(*c*) Many tholeiitic sills contain orthopyroxene in their lower portions at higher levels richer in volatiles. An indication is thereby given of pyroxene crystallisation under dry and wet conditions.

(*d*) Most dolerite sills have well-defined chilled contacts in which phenocrysts indicate the nature of the pre-injection crystallates and outline the early cooling history of the magma. Other contacts, however, are gradational and show interesting transfusion phenomena, but this applies with equal force to dykes.

(*e*) The intrusion temperature of dolerite and its volatile content are marginal in so far as palingenesis, rheomorphism and metasomatism of contact sediments are concerned.

*Mechanism of Crystallisation Differentiation.*

Gravitational settling of the early crystallates seems to be the main process of crystallisation differentiation. All of them are denser than the magma in which they crystallise and may settle either as discrete crystals or as aggregates of more than one mineral, e.g., pyroxene and calcic plagioclase (Jaeger and Joplin, 1955). They will then accumulate on the upward-growing floor of the intrusion, forming rock types rich in pyroxene or olivine. Plagioclase being only slightly denser than the magma, shows much less tendency to settle.

Olivine may settle from either tholeiitic or olivine dolerites to produce picrite dolerite or picrite, but significant sinking of pyroxene is found not only intholeiitic sheets such as the Palisades (Walker. 1940) and Mount Wellington (Edwards, 1942, 466-471). In olivine dolerite magma pyroxene is of relatively later crystallisation than either olivine or plagioclase and does not accumulate by gravity (Walker, 1957).

Hess (1956) has argued that the differentiation of the Palisades and other tholeiitic sheets showing a downward increase in pyroxene, may be the result of normal crystallisation plus convectional circulation without sorting, but some of his data are not confirmed by the observations of other workers (in particular, the relative tihckness of the upper and lower chilled phases).

One feature of differentiated sills which has not received enough attention is the complications introduced by the later injections of undifferentiated magma which I have termed "cognate". They are very common, but, being difficult to detect in the field, have escaped notice (Walker. 1957a, 90). Even the type examples of the Palisades and Shiant Isles are not free from them and I have found them in every dolerite province in which I have carried out detailed work. They are still more common and considerably easier to detect in dykes, e.g., those of the Cape Peninsula (Walker, 1957a, 78-80). Internal contacts are always sharp but may or may not be chilled. Apparently the magma, having once opened up in a channel, is followed by subsequent impulses without difficulty, sometimes along the join system, but more often taking independent courses. They are generally of insignificant volume compared with the original injection and differ therein from true multiple intrusions which seem to be confined to the vicinity of the plutonic centres associated with flood basalts.

Residual injections in sills (and dykes) are again insignificant in bulk, but are of the greatest interest as indicators of the differentiation trend. They occur as veins, schlieren or irregular patches either conformable to the contact or cross-cutting . Those in olivine dolerite intrusions grade through alkaline dolerite pegmatite into syenitic modifications with abundant analcite and nephaline, whereas in tholeiitic bodies the variation is through quartzose dolerite pegmatite into granophyric and felsitic types, the final stage being a quartz-albite rock. The mechanism of segregation and injection is not clear, but some of the latest veins seem to be hydrothermal replacement products rather than orthomagmatic.

**Palingenesis, Rheomorphism and Metasomatism of Contact Sediments**

Though the intrusion temperature of dolerite is generally in the neighbourhood of 1,100° C. and the initial fusion temperature of shale, arkose or siltstone (which are the most common contact sediments) some 400° C. lower, there is very little melting or mobilisation of the country rock in most dolerite suites. According to Jaeger's calculations, a temperature of over 630° C. cannot be reached in the contacts of a dolerite sill (1957, 310), but the field evidence is against this. In cases where the contact rock is fused more or less completely, tridymite is found fringing residual quartz grains. The inversion point between tridymite and high-temperature quartz is 867° C. and the change is sluggish so that a much higher temperature than 630° C. seems indicated. Tridymite is also found in unfused contact hornfelses. Let us now consider the phenomena observed.

*Palingensis,* or pure melting of contact sediments by dolerite is not a common phenomenon, though it has been recorded from several provinces. In no case is fusion more than local and it is confined to the immediate contact or to sedimentary xenoliths. The fused material seems always to be of quartzo-feispathic composition with quartz generally in excess of eutectic proportions. Excess $Al_2O_3$ goes to make cordierite. Glass disappears a few feet from the contact and fully-vitrified specimens have the appearance and chemical composition of pitchstone.

*Rheomorphism* is a much more common phenomenon than palingenesis and in certain provinces such as the Karroo it may be seen at the majority of well-exposed contacts. The mobilised sediment may be quartzo-felspathic, pelitic or semi-pelitic and, though a certain amount of transfusion and syntexis may take place, the sedimentary veins in the igneous rock resemble closely the baked sediments from which they have come. There may, however, be a tendency towards flueion structure. Though the evidence in favour of mobilisation is clear and convincing, the mechanism by which it was brought about is not yet clear. No glass occurs and the development of the liquid phase necessary to produce flow must have been quite slight in view of the resemblance between veins and contact sediment. Occasionally mobilisation is accompanied by marked transfusion with the production of gradational contacts (Walker and Poldervaart, 1943, 63; Drever and Johnston, 1957). Even in the best developed cases the volume of the material mobilised is minute compared with that of the igneous rock so that the temperature necessary to produce mobilisation cannot have been greatly exceeded.

Some dolerite provinces appear to be magmatically dead but recent work on well-exposed contacts has shown that the mobilisation temperature has just been reached in the Whin Sill and Palisadan provinces (Walker, 1958).

*Metasomation* of contact sediments and xenoliths is in every way a much more important process capable of converting, under suitable conditions, very considerable volumes of sedimentary material into rocks of definitely igneous aspect. Metasomatised sediments are particularly prominent in the Karroo province, especially in the roofs and partings of sills, and were described by Rogers and du Toit (1909) as dioritic and granophyric modifications of dolerite. Both the fabric and mineralogy of these rocks might well be taken as igneous either in the field or in thin section, but detailed examination reveals sedimentary structures and associations. Thus partings show residual kernels of unaltered sediment and granophyre which may be traced laterally into siltstone along blocks which have become partially detached from the upper contact (Walker and Poldervaart, 1942; 1949, 674-684).

The metasomatic process involves transfusion of caferric oxides into the sediment and of silica into the dolerite. The sediments affected are almost invariably siltstone and are enriched in iron, soda or potash, according to the magmatic stage reached at the time. A marked feature of these metasomatised siltstones is the development of elongated prisms of pyroxene nearly always serpentinised.

Metasomatism may be accompanied by mobilisation and rheomorphic veining of the igneous rock but in other cases delicate sedimentary structures such as small clay pellets are perfectly preserved.

Probably the most important feature of metasomatism is its quantitative aspect. This is well illustrated by the dolerite sill of Rietkop in the Karroo, which has almost completely metasomatised into granophyre a 70-feet parting of siltstone leaving unaffected only a few residual kernels of baked sediment. *Thus a dolerite sill in certain circumstances may transform one third of its own bulk of typical sedimentary material into rock of definitely igneous appearance and chemical composition.*

One may well ask what happens at depth and consider the case of the great "gap dykes" of the Transkei which Mountain (1944) considers to be of metasomatic origin at lower levels. If such widespread phenomena are produced by relatively small stratiform masses, what will be the fate of a tectogene immersed in sima? Even in dolerite provinces where there is an apparent absence of rheomorphic and metasomatic phenomena, the critical physico-chemical conditions for their initiation, are as mentioned above, closely approached.

**Depth of Lateral Injection**

It has frequently been suggested that the depth of sheet and sill injection may be governed by hydrostatic control, but we have seen already that the evidence is by no means clear. Every stratigrapher is familiar with the difficulty of drawing satisfactory isopachs and in the case of lateral hypabyssal injection there is the additional complication of placing flat-lying intrusions correctly in the eruptive time sequence. Vesiculation of margins may help and once more the Karroo province provides an instructive example. Lombaard (1953, 176), observed that dolerite dykes below the Cave sandstone (the highest sedimentary division of the Karroo System) are unvesiculated, whereas those in the sandstone have vesicular margins. He draws the logical conclusion that the latter were injected under a light load. Assuming that the overlying Stormberg lava plateau was in existence when the dykes were emplaced, we may arrive at a very approximate estimate of 5,000 feet as the depth of cover necessary to inhibit marginal vesiculation. This figure is obtained by adding the thickness of the Cave Sandstone to that of the lava pile in the area of Lombaard's investigations. Although tentative, this figure is in keeping with observations made in other provinces such as the Scottish Carboniferous and the Palisadan. Unfortunately, I have no data covering the Great Sill Group of Skye, which seems the most promising field for further investigation. If the critical depth for the inhibition of vesiculation can be established and shown to be reasonably constant in spite of the variables involved, it will be a very useful yardstick for the study of hydrostatic control as the governing factor in sheet injection.

**Tholeiitic and Olivine Basaltic Provinces**

I cannot leave this brief and somewhat disordered survey of hypabyssal vulcanism without some reference to the relationship between the two fundamental magma-types of kratogenic outbursts, the tholeiitic or normatively saturated basalts and the unsaturated olivine basalts. Until a few years ago opinion seemed to be trending towards the idea that the tholeiitic basalts and dolerites were invariably associated with the sialic continental blocks and were absent from oceanic islands beyond the folded arcs. The name "sub-sialic" was proposed for them (Wells and Wells 1948) and their origin through sialic contamination of sima was thought likely. Kennedy and Anderson (1938) advanced an hypothesis of crustal layering by which magma reservoirs of great lateral extent were formed by the fusion at appropriate depths of layers of different composition in a down-warped section of the crust. Thus tholeiite magma might be generated at the top of the "upper intermediate layer" while olivine basalt magma would be formed at the top of the "lower intermediate layer". In the foreland and hinterland areas fusion would be confined to the olivine basalt layer. Anderson considers the "lower intermediate layer" to be graded with increase of density downwards.

MacGregor (1948, 144-145), applying this hypothesis to the Scottish Carbo-Permian province, went a step further and, accepting Anderson's concept of grading, considers it probable that fusion took place at different levels at different times and never simultaneously as postulated by Kennedy (in Kennedy and Anderson, 1938, 40). Thus the alkaline olivine basalts and dolerites of the Lower Carboniferous were succeeded by tholeiites and quartz dolerites at the close of the Carboniferous and again by olivine basalt magma in the early Permian.

**CRUSTAL LAYERS IN NON-OROGENIC REGION**

(*After MacGregor*, 1948; *Kennedy and Anderson*, (1938.)

(NOTE.—Magma may originate by crustal fusion at A, B, or C.)

| | | |
|---|---|---|
| GRANATIC LAYER (11 km.) | | Essentially homogeneous |
| UPPER INTERMEDIATE LAYER (18 km.) | Tholeiitic (olivine-free or olivine-poor) basalt C | Essentially homogeneous |
| LOWER INTERMEDIATE LAYER (6 km.) | Alkaline —— B Olivine basalt A | Graded more mafic downwards |
| LOWER LAYER | Ultrabasic rock | |

A new aspect of the problem was presented by Tilley (1950) who pointed out that tholeiitic magma was by no means confined to the continents and occurred in mid-oceanic islands such as Réunion and Hawaii where the absence of sial seems fairly certain. He considered further that tholeiitic magma might arise by crystallisation differentiation of sima at depth under suitable conditions. Since then there has been no major contribution to the problem, though Battey (1956) has established an interesting link between the tholeiitic and spilitic suites in New Zealand.

Let us now turn back to the state of the problem in 1928, when Bowen was dealing with the magma-types of Mull, in particular with the Hebridean Plateau or olivine basalt and Non-Porphyritic Central or Tholeiitic magma-types. Bowen (1928, 74-76), basing his calculations on the averages given in the Mull Memoir (Bailey and Thomas, 1924, 14, fig. 2), shows by means of an addition and subtraction diagram that the most basic material which can be subtracted from the olivine basalt magma-type to produce the tholeiitic consists normatively of olivine, diopsidic pyroxene, calcic plagioclase and magnetite. All these appear amongst the early crystallates of basalt and could take part in processes of crystal fractionation. This was considered to be a strong argument for the derivation of the tholeiitic magma-type from the olivine-basaltic by fractional crystallisation. Kennedy, however, following Wahl (1933, 239), drew attention to the world-wide distribution of the tholeiitic type which he considered to be primary.

Daly also criticised Bowen's arguments, pointing out that the average chemical compositions of the two magma-types as given in the Mull Memoir are not reliable since they include abnormal and amygdaloidal types and are not quoted 100 per cent anhydrous. Furthermore, the normative composition of the subtracted material shows an olivine and pyroxene too ferriferous and a plagioclase too sodic to appear amongst the earliest crystallites (Daly, 1933, 399; 1944, 1394).

Some years ago I recalculated the normative composition of the subtracted material, using weeded averages in which some additional analysis had been incorporated and the results are given below, together with Bowen's:—

| | Bowen. | % | Walker. | % |
|---|---|---|---|---|
| Olivine | $Fa_{37}$ | 27 | $Fa_{26}$ | 18 |
| Pyroxene | $Wo_{51}En_{29}Fs_{20}$ | 7.5 | $Wo_{22}En_{62}Fs_{16}$ | 17.5 |
| Plagioclase | $An_{63}$ | 53 | $An_{80}$ | 53 |
| Magnetite | ... | 4.5 | .... | 10.5 |

The recalculated normative compositions are much more in keeping with the anticipated compositions of the earliest crystallates and Bowen's solution of the problem may be kept in mind therefore, pending the accumulation of further and more convincing data.

In conclusion, if Kennedy's postulate of two world-wide and primary basalt magma-types is valid, material transitional between the two fundamental types should be of relatively small bulk. Though no quantitative estimates are available this seems to be the case. Transitional provinces are scarce though they are to be found; e.g., the basalts of Central Victoria.

Having briefly surveyed the hypabyssal basaltic rocks of the world and the problems which they present, let us leave them with one aspect on which all petrological disputants will agree—the wonderful scenery of their terrains which finds its most spectacular development in the lovely island of Tasmania where R. M. Johnstone compiled his monumental work.

### REFERENCES.

ANDERSON, E. M., 1951.—The Dynamics of Faulting (2nd ed.), Edinburgh.

BAILEY, E. B., AND THOMAS, H. H., 1924.—The Tertiary and pre-Tertiary Geology of Mull. *Mem. Geol. Survey, Scotland.*

BATTEY, M. H., 1956.—The Petrogenesis of a Spilitic Rock Series from New Zealand. *Geol. Mag.*, 93, 89-110.

BOWEN, N. L., 1928.—The Evolution of the Igneous Rocks, Princeton.

DALY, R. A., 1933.—Igneous Rocks and the Depths of the Earth. New York.

————, 1944.—Volcanism and Petrogenesis as Illustrated in the Hawaiian Isles. *Bull. Geol. Soc. Amer.*, 55, 1363-1400.

DREVER, H. I., AND JOHNSTON, R., 1957.—The Lower Margin of the Shiant Isles Sill (Outer Hebrides). *Proc. Geol. Soc. London*, 1555, 12.

DU TOIT, A. L. 1954.—The Geology of South Africa (3rd ed.), Edinburgh.

EDWARDS, A. B., 1942.—Differentiation of the Dolerites of Tasmania. *Journ. Geol*, 50, 451-480 and 579-610.

HARKER, A., 1904.—The Tertiary Igneous Rocks of Skye. *Mem. Geol. Survey, Scotland.*

HESS, H. H., 1956.—The Magnetic Properties and Differentiation of Dolerite Sills—A Critical Discussion. *Amer. Jour Sci.*, 254, 446-451.

HOTZ, P. E., 1952.—Form of Diabase Sheets in South Eastern Pennsylvania. *Amer. Jour. Sci.*, 250, 375-388.

JAEGER, J. C., 1957.—The Temperature in the Neighbourhood of a Cooling Intrusive Sheet. *Amer. Jour. Sci.*, 255, 306-318.

JAEGER, J. C. AND JOPLIN, G. A. 1955.—Rock Magnetism and the Differentiation of a Dolerite Sill. *Journ. Geol. Soc. Aus.* 2, 1-19.

KENNEDY, W. G.. 1931.On Composite Lava Flows. *Geol Mag.*, 68, 166-181.

——————, 1933.—Trends of Differentiation in Basaltic Magmas. *Amer. Jour. Sci.*, 25, 239-256.

KENNEDY, W. G., AND ANDERSON, E.M., 1938.—Crustal Layers and the Origin of Magmas. *Bull. Volc. II.*, 3, 24-82.

KOOMANS, C., AND KUENEN, P. H., 1938.—On the Differentiation of the Glen More Ring Dyke. *Geol. Mag.*, 75, 145-160.

LOMBAARD, B. V., 1953.—Karroo Dolerites and Lavas. *Trans. Geol. Soc. S. Af.*, 55, 175-198.

MACGREGOR, A. G., 1948.—Problems of Carboniferous-Permian Volcanicity in Scotland. *Quart. Journ. Geol. Soc.*, 104, 133-154.

MOUNTAIN, E. D., 1944.—The Dykes of the Transkei Gaps. *Trans. Geol. Soc. S. Af.*, 46, 55-74.

POLDERVAART, A., 1944.—The Petrology of the Elephants Head Dyke and the New Amalti Sheet (Matatiele). *Roy. Soc. S. Afr. Trans.*, Vol. 30, 85-119.

READ, H. H., 1957.—The Granite Controversy, London.

RICHEY, J. E., 1932.—Tertiary Ring-structures in Britain. *Trans. Geol. Soc. Glasgow.* 19, 42-140.

——————, 1939.—The Dykes of Scotland. *Trans. Geol. Soc. Edin.*, 13, 393-435.

ROGERS, A. W., AND DU TOIT, A. L., 1909.—The Geology of Cape Colony (2nd ed), London.

SCHOLTZ, D. L., 1937.—The Magmatic Nickeliferous Ore Deposits of East Griqualand and Pondoland. *Trans. Geol. Soc. S. Af.*, 39, 81-210.

TILLEY, C. E., 1950.—Some Aspects of Magmatic Evolution. *Quart. Journ. Geol. Soc.*, 106, 37-61.

TOMKEIEFF, S. I., 1937.—Petrochemistry of Scottish Carboniferous-Permian Igneous Rocks. *Bull. Volc., II.* 1, 58-97.

TYRRELL, G. W., 1928.—The Geology of Arran. *Mem. Geol. Survey, Scotland.*

——————, 1937.—Flood Basalt and Fissure Eruptions. *Bull. Volc. II*, 1, 89-111.

WALKER, F, 1940.—Differentiation of the Palisade Diabase, New Jersey. *Bull. Geol. Soc. Amer.*, 51, 1059-1106.

——————, 1957.—Ophitic Texture and Basaltic Crystallisation. *Journ. Geol.*, 65,1-14.

——————, 1957a.—The Dolerite Dykes of the Cape Peninsula. *Trans. Geol. Soc. S. Af.*, 59, 77-94.

WALKER, F., AND POLDERVAART, A., 1942,—The Metasomation of Karroo Sediments by Dolertie. *Trans. Roy. Soc. S. Af.*, 29, 285-307.

——————, 1943.—The Karroo Dolerites of the Calvinia District. *Trans. Geol. Soc. S. Af.*, 44, 55-64.

——————, 1949.—Karroo Dolerites of the Union of South Africa. *Bull Geol. Soc. Amer.*, 60, 591-706.

WELLS, A. K. AND M. K., 1948.—On Magma Types and Their Nomenclature. *Geol. Mag..* 85, 49.