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Author(s): George P. L. Walker
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ZEOLITE ZONES AND DIKE DISTRIBUTION IN RELATION TO THE STRUCTURE OF THE BASALTS OF EASTERN ICELAND[1]

GEORGE P. L. WALKER
Imperial College, London

ABSTRACT

Amygdale minerals in the Tertiary basalt lavas of eastern Iceland have a well-marked zonal distribution; the flat-lying zones mapped in the field bear no relationship to the lava stratigraphy and are inferred to be approximately parallel to the original top of the lava pile. An independent method of deducing the position of this is available, depending on the fact that the intensity of the Tertiary dike swarm in the area everywhere diminishes upward; extrapolation gives the altitude of zero intensity, which is in good agreement with the altitude of the original top of the lavas deduced from the mineral zones. Both support the observation that the lavas thin up-dip, and the implications of this on the interpretation of the structure and geology of Iceland are discussed.

INTRODUCTION

Zeolites and other amygdale minerals are extremely abundant in the Tertiary basalt lavas of eastern Iceland. During the course of geological mapping over the last six years, it has become clear that these minerals have a regular distribution; they occupy flat-lying zones which bear no relationship to the stratigraphy of the lava pile.

Associated with the lavas, there is an intense swarm of dikes. The dikes represent the feeding channels of the lavas. The large amount of quantitative data which has now been collected indicates that the intensity of the dike swarm everywhere diminishes upward.

In this paper it is shown how data on these two apparently unconnected phenomena—zoning of the amygdale minerals and vertical variations in intensity of the dike swarm—may be integrated with stratigraphic data to produce a unified picture of the geological structure and history of Iceland. The inference is made that knowledge of the distribution of secondary minerals and dikes is essential in the interpretation of any area of flood basalts.

The zonal distribution of amygdale minerals and the distribution of dikes have been studied by the writer over an area of 1,000 square miles in eastern Iceland. In this paper a more restricted area (indicated in the index map, fig. 1) has been selected to illustrate the relationships, comprising the mountain ridge lying between Berufjördur and the broad valley of Breiddalur to the north. To complete the picture, brief reference is also made to exposures further inland, in Jökuldalur and Fljótsdalur.

GEOLOGICAL SETTING

The geology of the Berufjördur-Breiddalur area is essentially similar to that of Reydarfjördur (Walker, 1959). The thick Tertiary volcanic succession is predominantly of tholeiite lavas, but it includes groups of olivine-basalt and feldspar-porphyritic basalt lavas. The succession is inclined to the west or southwest; the dip measured at sea level is in the range 5–10°. Systematic stratigraphic mapping by the writer has established the absence of major faults and thus eliminated the possibility of repetition of the lava sequence. Adding together the average exposed thickness of each stratigraphic unit, a total thickness of the order of 15,000 feet is obtained for the lavas within the confines of the map (fig. 2), constituting approximately half of the complete Tertiary succession in eastern Iceland. The up-dip thinning of the lavas is considered in a later section.

A major complication in this otherwise straightforward dipping sequence is the presence of a buried Tertiary volcano in upper Breiddalur, partly exhumed by ero-

[1] Manuscript received February 16, 1960.

sion, which is marked by a great thickness of thin tholeiite and andesite lavas, together with thick acid flows and tuffs. The lavas from this volcanic center interdigitate with the flood basalts of the surrounding country and in part form a shield which has subsequently been buried by later regional flood basalts. However, these stratigraphic complications do not materially affect the thesis presented in this paper.

Dikes with a predominant N.NE. trend are very abundant and are considered to represent the feeders of the lavas. The number of dikes at sea level in the 23-mile strip of country in figure 4 is estimated at 450, with an aggregate thickness of 7,500 feet (2,300 meters). Dikes are concentrated in two narrow belts, both with a N.NE. trend, of which one passes through the Breiddalur volcanic center, and the other, near the mouth of Berufjördur, is related to a Tertiary volcanic center to the south.

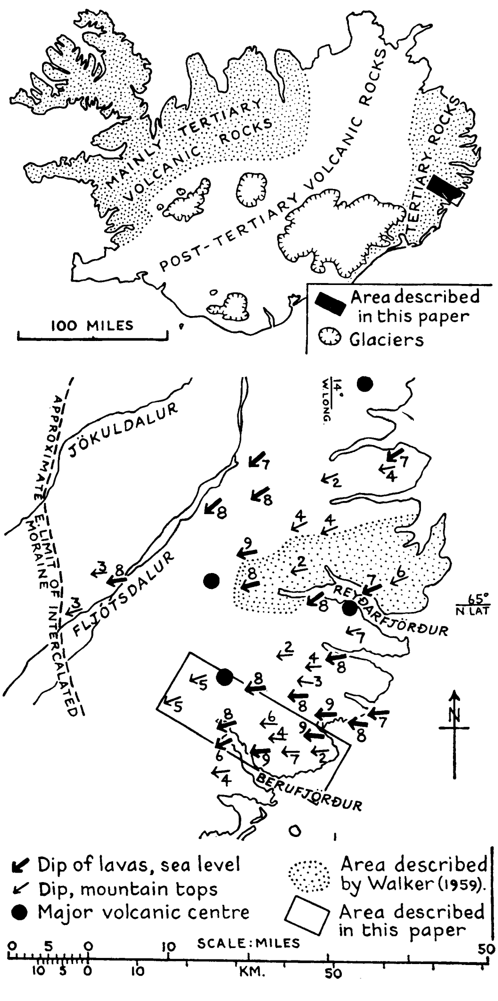

FIG. 1.—Berufjördur-Breiddalur area in relation to the Tertiary volcanic outcrop in eastern Iceland. The lower map illustrates also the general upward decrease in dip of the lavas.

AMYGDALE MINERALS AND THEIR DISTRIBUTION

Berufjördur has long been famous for its zeolites—especially noteworthy are stilbite, heulandite, epistilbite, and scolecite. The following is a list of the mineral species which have been identified:

Zeolites		Non-Zeolites	
Analcime	VA*	Apophyllite	C
Chabazite	VA	Aragonite	R
Epistilbite	C	Calcite	VA
Erionite	R	Celadonite	C
Gismondine	R	Chalcedony and opal	VA
Heulandite	VA	Chlorite	C
Laumontite	C	Epidote	R
Levyne	C	Gyrolite	C
Mesolite	VA	Okenite	R
Mordenite	VA	Quartz	VA
Phillipsite	C		
Scolecite	VA		
Stilbite	VA		
Thomsonite	VA		

* VA = very abundant; C = common; R = rare.

Of the above, gyrolite and gismondine appear to be new records for Iceland, and perhaps epidote and okenite are also; levyne and phillipsite appear to be new records for the Tertiary fiordlands of East Iceland. The present writer has not found erionite in the area.

In addition to the above minerals, small crystals of the pyrogenetic minerals of the basalt (plagioclase, augite, magnetite, ilmenite, and apatite) are sometimes encountered growing into amygdales, and the acid rocks sometimes contain tridymite and cristobalite.

The assemblage of secondary minerals in olivine-basalt lavas differs fundamentally

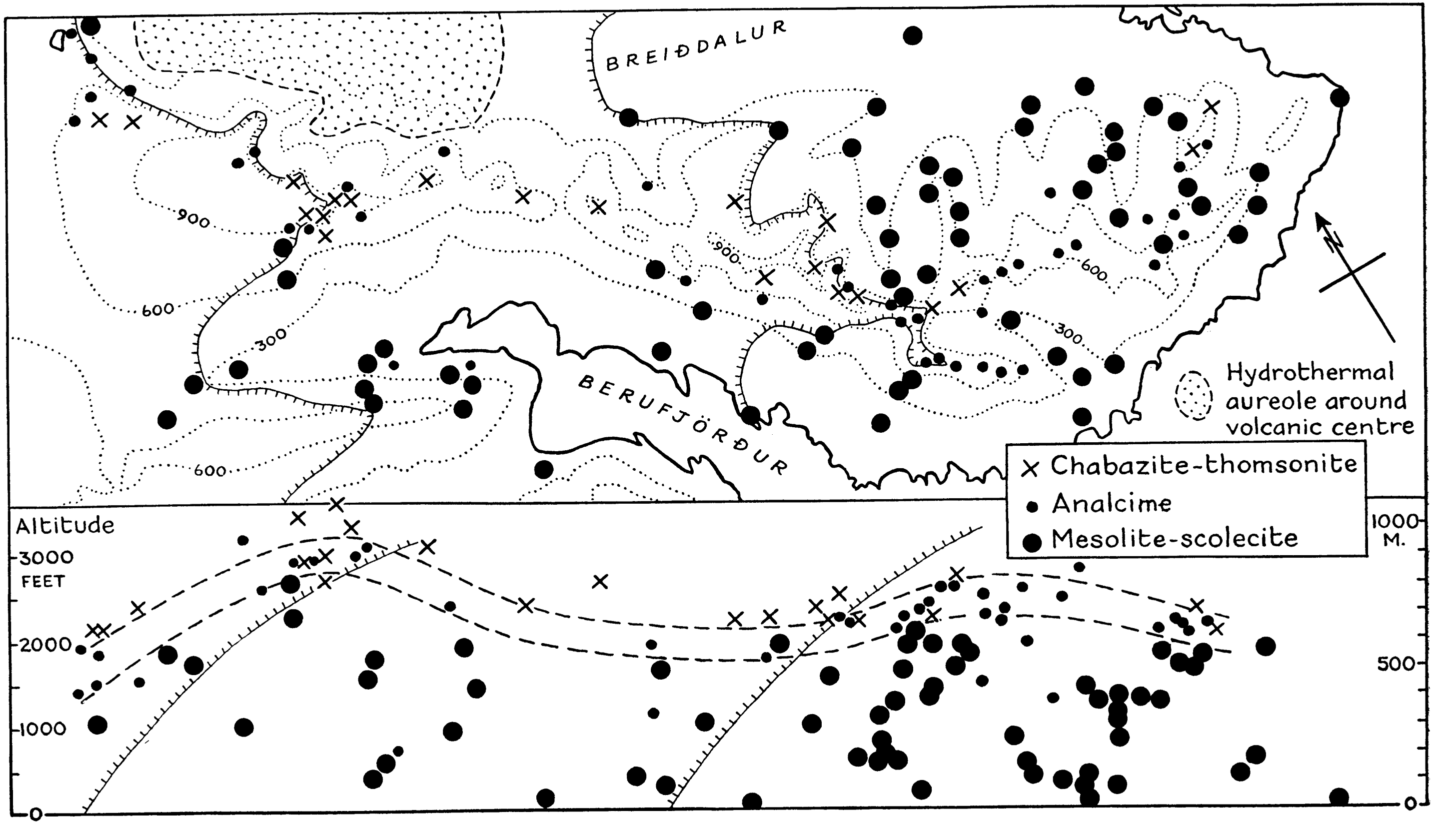

FIG. 2.—Distribution of amygdale minerals in the Tertiary olivine-basalt lavas in the Berufjördur-Breiddalur area

from that in tholeiite lavas, and in the following study the minerals in these two rock types are considered separately.

REGIONAL DISTRIBUTION OF ZEOLITES IN OLIVINE-BASALT LAVAS

Outside the several known areas of hydrothermal alteration about Tertiary volcanic centers, the olivine-bearing lavas are very rich in zeolites, together with variable but usually minor amounts of calcite, apophyllite, and gyrolite. Of the zeolites the relatively silica-poor species (thomsonite, chabazite, analcime, mesolite, levyne, and phillipsite) are the most prominent, and mordenite and epistilbite are never encountered. Quartz and chalcedony are likewise missing.

The zeolites occupy flat-lying zones, the distribution of which is readily mapped, each zone being characterized by a distinct assemblage of minerals. The sequence of zeolite zones in olivine-basalt lavas has now been established over a large part of the Tertiary basalt outcrop in eastern Iceland.

A lowest zone rich in mesolite and scolecite (fig. 2) extends from below sea level to a maximum altitude of about 2,500 feet. It is in this zone that zeolitization is most intense and the number of mineral species is greatest; the mesolite and scolecite are typically accompanied by chabazite, thomsonite, analcime, stilbite, heulandite, apophyllite, and gyrolite, and sometimes by levyne and laumontite. Laumontite is found low down but is too erratic in distribution to enable a separate laumontite zone to be mapped. Zeolites are not confined to amygdales but permeate the whole rock, occupying angular interspaces between the pyrogenetic mineral grains and often replacing the feldspar.

Above the mesolite zone comes a zone some 500 feet thick, in which analcime is the characteristic index mineral. Mesolite persists into this zone, but it is much less abundant and forms clusters of delicate, hairlike fibers in place of the compact amygdale fillings of the mesolite zone. Stilbite and heulandite are much less abundant at that depth, and chabazite, thomsonite, levyne, and phillipsite are more prominent. The top of the analcime zone is readily located in the field, being marked by the disappearance of analcime and also of mesolite, stilbite, and heulandite.

Above the analcime zone the lavas contain a restricted zeolite assemblage comprising mostly chabazite and thomsonite, together with levyne and phillipsite and some calcite, apophyllite, and gismondine. Phillipsite is most prominent in the lower few hundred feet, although it does not seem practicable to map a distinct phillipsite-rich zone. Not only is the chabazite-thomsonite zone poorer in species than the zones below it, but the intensity of zeolitization is lower. In the eastern fiordlands of Iceland the chabazite-thomsonite zone extends up to the top of the mountains.

The zeolite zones clearly cut across the stratification of the lavas (fig. 2), and many stratigraphic groups of olivine-basalt lavas have been followed by the writer from the mesolite zone through the analcime zone and into the chabazite-thomsonite zone. Although the interzone surfaces are undulating, they fall gradually in altitude toward the west (fig. 5), and exposures near the top of the Tertiary lava pile in Jökuldalur and Fljótsdalur show the top of the analcime zone at the level of the valley floor, if at all. Above it comes a zone bearing the chabazite-thomsonite assemblage. The intensity of zeolitization falls off upward in this zone. Phillipsite, levyne, calcite, and apophyllite almost entirely disappear in the upper part, and the grain size of the chabazite decreases by a factor of $\frac{1}{2}$ or $\frac{1}{4}$. Finally, some 1,300 feet above the top of the analcime zone, zeolites disappear entirely, and thereafter the basalts have empty vesicles.

The zeolite-free lavas in Jökuldalur and upper Fljótsdalur form a succession that is upward of 500 feet thick. The lavas are often inclined at a few degrees and the succession is cut through by deep valleys, and in these respects the lavas resemble Tertiary basalts; but intercalated with the lavas are palagonite tuffs, solifluxion sheets with frost-heaving of the basalt floor, and, higher up, moraine resting upon a striated pavement. Eruption of this series of lavas must have continued into the early Quaternary. The succession has subsequently suffered erosion, but it is unlikely that more than a few hundred feet of rock have been eroded away from the plateau surface, and a figure of 700 feet for the original thickness of lavas above the top of the chabazite-thomsonite zone cannot be far from the truth. This 700 feet must represent the blanket below which zeolites were able to form.

REGIONAL DISTRIBUTION OF MINERALS IN THOLEIITE LAVAS

Quartz, chalcedony, mordenite, chlorophaeite, celadonite, and epistilbite in the basalt lavas of eastern Iceland are virtually confined to the tholeiites, and all but the last are extremely abundant. Stilbite and heulandite are much more abundant in tholeiite lavas than they are in the olivine basalts. On the other hand, chabazite and thomsonite are seldom encountered in the tholeiites, and analcime, phillipsite, levyne, gismondine, and gyrolite are almost never found.

The minerals in tholeiite lavas form zones which are approximately parallel to those in the olivine basalts (fig. 3). In the lowest zone, extending to a maximum of rather more than 1,000 feet above sea level, zeolites are abundant, associated with quartz and chalcedony. It is in this lowest zone that the magnificent specimens of stilbite, heulandite, scolecite, and epistilbite, for which Berufjördur is famous, are found. The well-known locality of Teigarhorn is on the south shore of Berufjördur near its mouth, just off the area of the map (fig. 3).

Above the lower, zeolite-rich, zone the tholeiite lavas to an altitude of as much as 2,500 feet contain chalcedony, quartz, and mordenite, together with widespread chlorophaeite and celadonite.[2] These minerals are rather erratically distributed but decrease in amount upward. Above a certain level, the exact position of which is not readily defined but which is near the top of the analcime zone in the olivine basalts, the tholeiite lavas have empty vesicles.

INTERPRETATION OF REGIONAL ZONING

Regional zoning of amygdale minerals in Tertiary basalt lavas of the North Atlantic region was first demonstrated in the Antrim Basalts (Walker, 1951), and a similar, if thicker, series of zones is widespread in Iceland. Zoning of a broadly similar type has been established in the Lake Superior region (Stoiber and Davidson, 1959), and zones of low-grade regional metamorphism in the geosynclinal deposits of New Zealand (Coombs *et al.*, 1958), although differing in their geological setting, fall into a similar category. The successive zones, each with distinctive mineral assemblage, must reflect the temperature attained in the lavas during zeolitization. The zone boundaries must, in fact, mark the position of geoisotherms during this period. Experimental work should eventually enable the appropriate temperature values to be assigned to these geoisotherms, although it does not at present seem possible to do so.

The fact that the zone boundaries cross the lava stratigraphy is quite clear in Antrim and outstandingly so in Iceland. It establishes the late age of zeolitization: the zeolites and associated secondary minerals were obviously formed at a time long subsequent to the eruption and cooling down of the individual lavas. One can envisage geoisotherms rising in a lava pile which is gradually becoming thickened by outpouring of lavas on top. Below the water table the slaggy and vesicular flows are saturated with water,[3] and at those levels where, due to the steady rise of the geoisotherms, the appropriate temperature is attained, the ground water begins to react with basalt to produce zeolites and other secondary minerals.

[2] Stilbite, heulandite, and other zeolites may be developed in tholeiite lavas in this zone where immediately adjacent to a group of olivine basalts.

[3] The central Iceland desert is largely made up of postglacial basalt lavas; rain, when it falls, rapidly soaks into the lavas, and the drainage is largely subsurface, along the slaggy basalt horizons.

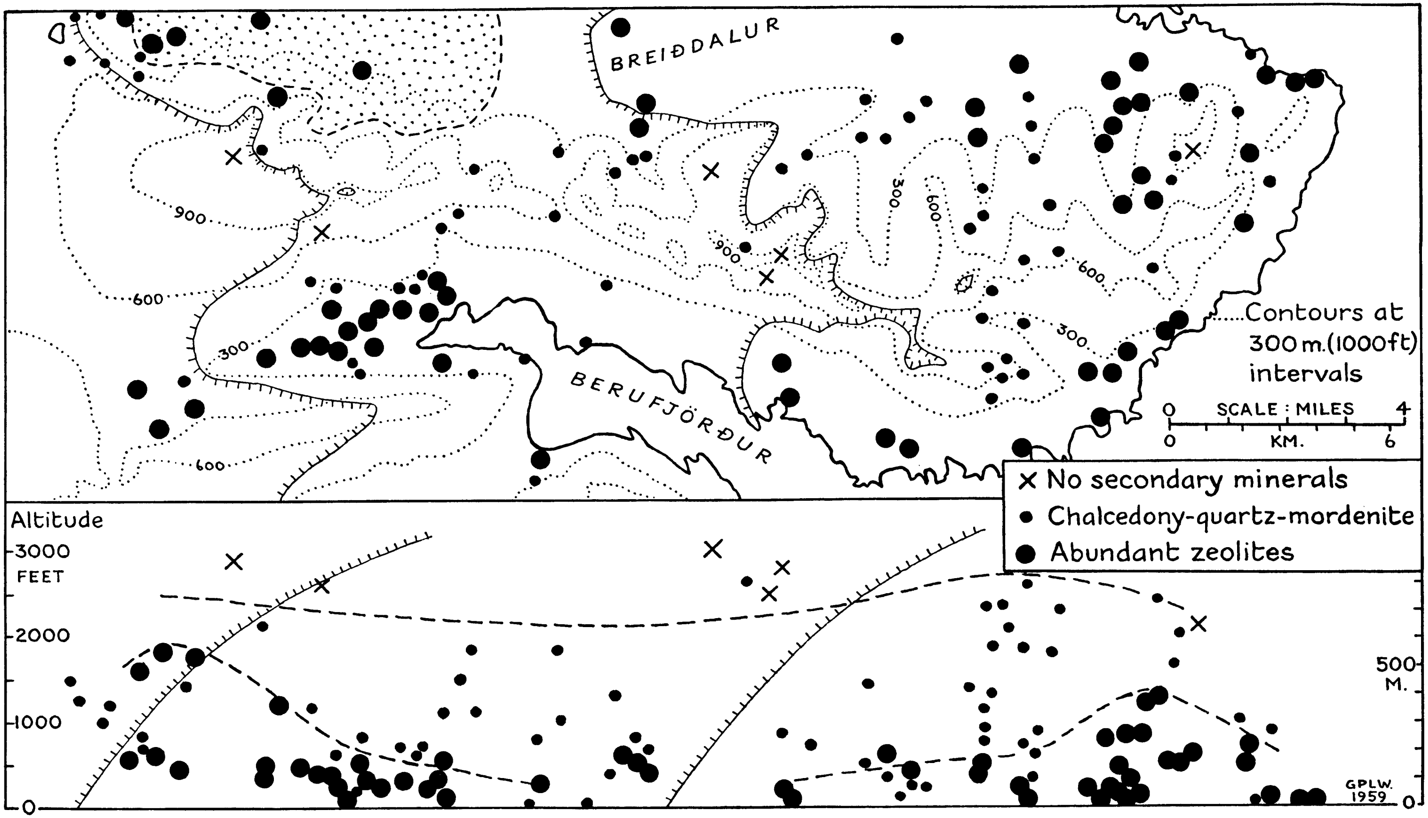

FIG. 3.—Distribution of amygdale minerals in the Tertiary tholeiite lavas in the Berufjördur-Breiddalur area. The structure of the lavas in figs. 2 and 3 is illustrated by two stratigraphic horizons plotted on both maps and sections.

As the geoisotherms rise thus, the top of the zone of zeolitization rises. Above it is a zone of basalts, acting as a blanket, in which the temperature is too low to permit zeolitization.

The heat to support zeolitization is supplied by dikes, by the slow accession of heat from below, and by exothermic hydration reactions in the lavas. The lavas merely supply the water-filled cavities and the required chemical raw materials.

In eastern Iceland it is considered that the zeolite zones are approximately parallel to the original top of the Tertiary basalt lava pile and represent the highest level attained by the geoisotherms before erosion started to reduce the thickness of the pile. Approximately 2,000 feet of lavas are indicated in Jökuldalur and Fljótsdalur as having overlain the top of the analcime zone. The figure may vary somewhat, being lower at those places where the geothermal gradient is unusually high. It is significant that the two zone culminations on the section of figure 2 coincide with the regions of greatest density of dikes: regions of unusually high geothermal gradient. On the sections of figure 4 and figure 5, *B*, a level 2,000 feet above the top of the analcime zone has been plotted, which is considered to represent the approximate position of the original top of the lava pile.

There seems no reason why the Icelandic experience should not be applied to other regions of flood basalts in which similar zoning is developed but in which parts of the upper zones have been eroded away. In Antrim and northern Skye, for instance, similar zoning is seen, but the tops of the mountains lie in the chabazite-thomsonite zone. It may be deduced, for instance, that in the Garron Plateau region in Antrim (Walker, 1951) the original thickness of lavas was about 2,500 feet, as compared with the present maximum exposed thickness of 1,000 feet.

COLOR ZONING OF THE ROCKS

Olivine-basalt lavas in the mesolite and analcime zones and in the lower part of the chabazite-thomsonite zone are very dark in color, which is due mainly to the presence of certain alteration products of olivine. The olivine basalts higher up are very pale in color due to the absence of these alteration products. Such pale-colored lavas are best developed high up in the Tertiary succession (for instance, in Jökuldalur and Fljótsdalur), but they are also encountered much lower in the succession on high mountains in the eastern fiordlands of Iceland, where these mountains reach 1,000 feet or more above the top of the analcime zone, as in Dagmálafjall, Snjófell, and Bjólfur, near Seydisfjördur, and in Skagafjall and Kambfell, near the western end of Reydarfjördur. The significance of this observation in the interpretation of the "Gray Stage" lavas of Iceland is discussed on page 524.

It is likely that many other effects may be correlated with the position of the zeolite zones. For instance, tholeiite lavas in the zeolite-rich zone are highly altered and correspondingly pale in color in contrast to the olivine-basalt lavas, while acid tuffs low down are almost invariably green in color due to the presence of celadonite, and pale gray or cream higher up where celadonite is missing. The condition of the chilled margins of acid flows may also be correlated, being invariably of pitchstone and devitrified pitchstone in the lower zeolite zones but sometimes including obsidian in the higher zones.

LOCAL ZONING OF AMYGDALE MINERALS

Quite distinct from the regional zones, it is possible to recognize and map local hydrothermal aureoles in and about major Tertiary volcanic centers. Four of these are now known in eastern Iceland (fig. 1). In each case there is a central region in which the lavas and most of the minor intrusions cutting them are severely altered ("propylitized") to pale green rocks rich in chlorite, calcite, and epidote. Amygdales in these rocks bear calcite, quartz, epidote, laumontite, and andracite. Surrounding these propylitized areas is a broad zone in which there is a great abundance of calcite.[4] Some

[4] The famous Iceland Spar mine at Helgustadir, Reydarfjördur, is in altered lavas on the edge of such a zone of propylitization.

of the calcite has a distinctive habit, being tabular on (0001), and some is in saccharoidal aggregates paramorphing aragonite.

In the Lón district of southeast Iceland, south of the area of figure 1, several of the large gabbro and granophyre intrusions (Cargill, Hawkes, and Ledeboer, 1928), which probably mark other volcanic centers, have inner aureoles in which amygdales bear garnet, pyroxene, amphibole, and epidote, and broad outer hydrothermal aureoles in which laumontite is prominent. A brief examination by the writer suggests that the outer aureoles are extremely extensive in this region.

THE DISTRIBUTION OF DIKES

In a recent paper (Walker, 1959) a method of quantitative study of a dike swarm was described in which the dikes in a strip of well-exposed country were counted and measured and the number of dikes per mile and the percentage stretch[5] or dilation, calculated. The method is not new, and literature on the British Tertiary volcanic province[6] includes a number of examples of such measurements. However, no attempt seems to have been made to study the vertical variation with height in the lavas. Essential prerequisites to such a study are good exposures and a considerable relief, and neither of these is lacking in the eastern fiordlands of Iceland.

During the course of geological mapping in eastern Iceland in the past five years, the intensity of the dike swarm has been studied in this way in 150 strips with total length of about 120 miles,[7] and everywhere the intensity of the swarm is found to be greatest at sea level, diminishing upward to something like half the intensity near the top of the mountains. The appropriate data for Berufjördur are presented on figure 4.

Data for the strips in each of 8 belts of country (*A* to *H* in fig. 4) parallel to the trend of the swarm are plotted on graphs, the percentage stretch and the number of dikes per mile being treated separately. The percentage stretch falls off more consistently upward than the number per mile, for the latter figure is dependent on the nature of the rocks through which the dikes have passed. The strip at 2,700 feet in band *D* of figure 4, for instance, was measured along the top of a group of andesite lavas. Some of the dikes passing through these highly fissile andesites have split into numerous thin stringers, and the figure for the number of dikes per mile is abnormally high as a result.

Assuming a linear variation, extrapolation gives the altitude of zero intensity of the dike swarm. Considering the crudeness of the method, the figures obtained for this altitude of zero intensity are surprisingly consistent, varying from about 5,000 to just under 4,000 feet above present sea level, with an over-all fall eastward. The reality of the upward decrease in intensity of the swarm has been established, and the only doubt attaches to the interpretation of the data. Assuming that the dikes are the feeders of the lavas, the altitude of zero intensity must coincide approximately with the original top of the lava pile.

The remarkably close agreement between the figures for the altitude of zero intensity is illustrated by the lower diagram of figure 4. The most noteworthy feature, however, is the equally close agreement with the position of the top of the lava pile deduced from the zeolite zones, also plotted on figure 4. Similar close agreement has been obtained for Reydarfjördur and other areas in East Iceland.

[5] Percentage stretch = aggregate thickness of dikes × 100/length of strip measured across trend of swarm.

[6] For example, in Mull (Bailey *et al.*, 1924), 375 dikes with an aggregate thickness of 2,500 feet occur in a section $12\frac{1}{2}$ miles long, giving an average stretch of nearly 4 per cent; the 142 dikes in one $1\frac{1}{4}$-mile section aggregate 817 feet in thickness and represent a stretch of 12 per cent. In Arran (Tyrrell, 1928) the dikes in 15 miles represent a total E.SE.–W.NW. stretch of 5,410 feet, the average stretch being 7 per cent. In the Mourne dike swarm (Tomkeieff and Marshall, 1935) 128 dikes give an average stretch over 7 miles of $2\frac{1}{2}$ per cent.

[7] The aggregate thickness of dikes in these strips amounts to some 25,000 feet.

DISCUSSION

THE THICKNESS OF THE TERTIARY LAVA PILE IN ICELAND

One of the striking features of the extensive Tertiary basalt lava piles of the North Atlantic region is their great thickness. In eastern Iceland, for instance, the lavas are inclined at 5° to 10° (the dip being measured at sea level) in a general westerly direction over a distance of 50 miles, and a thickness of the order of 30,000 feet is indicated.

Such figures are not peculiar to Iceland. A thickness of the order of 10 km. has been estimated for basalts of the same general age in West Greenland (Noe-Nygaard, 1942); 7.5 km. for basalts in East Greenland (Wager, 1947); and over 15,000 feet for the Faeroe Islands (Walker and Davidson, 1936).

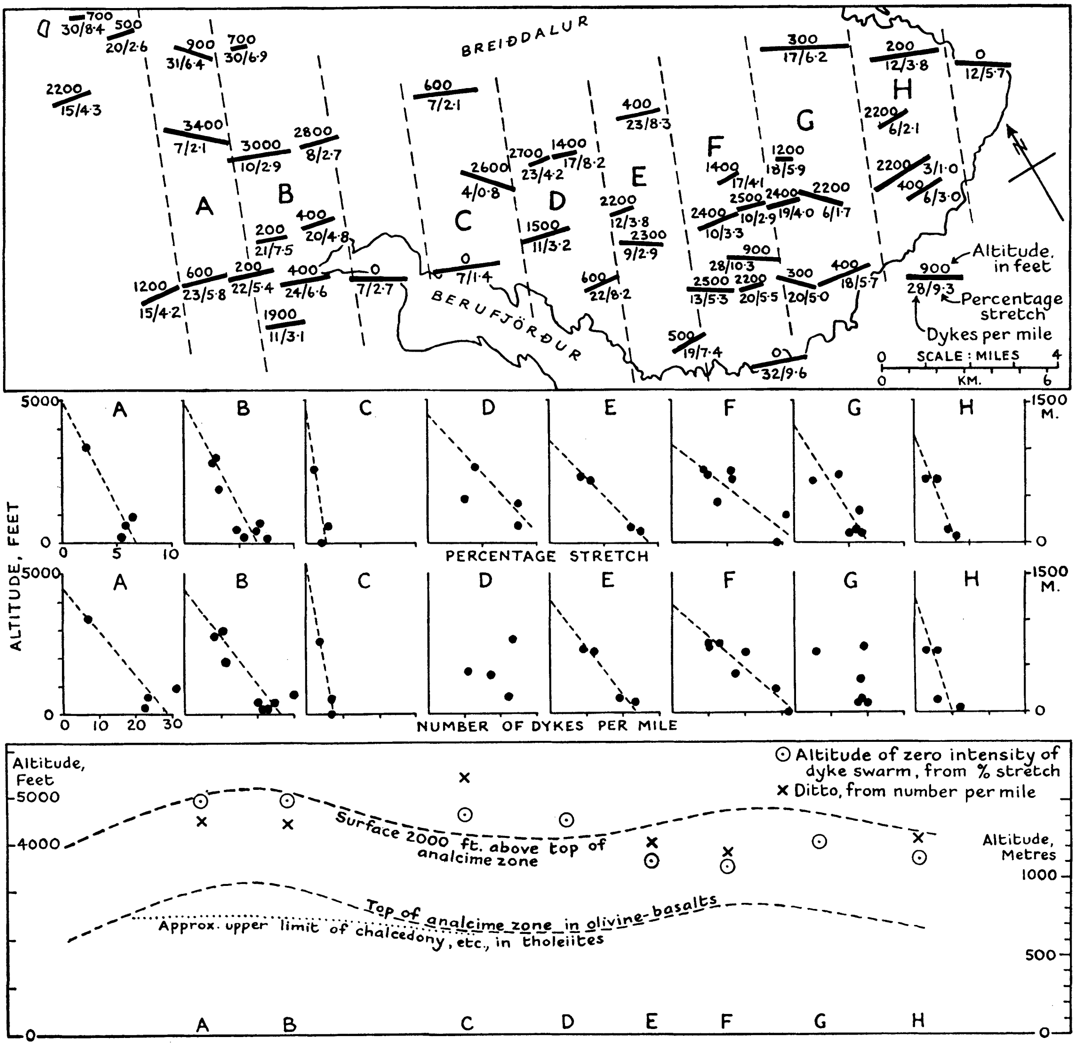

FIG. 4.—Quantitative study of the Tertiary dike swarm in the Berufjördur-Breiddalur area. The individual dikes have a predominant N.NE. trend. Data on acid dikes have been omitted from this study. The lower section compares the altitude of zero intensity of the dike swarm with the position of a surface 2,000 feet above the top of the analcime zone.

In eastern Iceland the available evidence indicates that the dip is essentially due to tilting. It has usually been tacitly assumed that the lavas form a parallel stratified succession. Such an assumption introduces serious difficulties. For instance, if 30,000 feet of lavas have been tilted, the best part of 30,000 feet must have been eroded away from the higher parts of the tilted block. Although reliable quantitative data on the rate of erosion are lacking, the time available since the outpouring of the lavas seems inadequate for the erosion of so great a thickness of basalt.

In the course of geological mapping in eastern Iceland during the past few years, the writer has amassed a large amount of evidence that the lavas thin up-dip by progressive reduction in the number of flows. A typical stratigraphic unit a few hundred feet thick decreases in thickness up-dip at the rate of 50 to 100 feet per mile, and the average rate of thinning is of the order of 5 per cent per mile. On the tops of the mountains the dip is usually found to be several degrees less than it is at sea level (figs. 1 and 5).

Granted such a rate of thinning of the lavas, it can be seen that the original top of the lava pile may have been little higher than the present-exposed lavas, and erosion has removed at most only a few thousands, instead of a few tens of thousands, of feet of rock. By extrapolating the observed rate of decrease in thickness beyond the present tops of the mountains, a figure of the order of 6,000 feet above present sea level is indicated for the position of the original top of the lava pile.

Study of the zoning of the amygdale minerals and of the vertical variation in intensity of the dike swarm enables the position of the original top of the lava pile to be deduced. The close agreement in the results from two such independent methods, as shown on the lower section of figure 4, clearly indicates the validity of the methods. Extrapolation of the stratigraphic data beyond the limits of the present exposures cannot be undertaken with any confidence; although suggesting a position for the top of the lava pile somewhat higher than that deduced from zeolite and dike data, the results from the three methods are in sufficiently close agreement to be accepted. The inferred relationships between the lava stratigraphy and the zeolite zoning are presented diagrammatically on the sections of figure 5.

It can be seen that it is necessary to define very carefully what is meant by the thickness of the volcanic succession. Four possible values for the thickness are illustrated by figure 5 as follows:

a) the sum of the average exposed thickness of each individual stratigraphic unit (about 30,000 feet in eastern Iceland)
b) the sum of the maximum exposed thicknesses of stratigraphic units (about 35,000 feet)
c) the minimum thickness, *c* (about 5,000 feet, plus an unknown amount for the extension of the lavas below sea level), at the eastern end of the Tertiary outcrop
d) the maximum thickness, *d* (well over 30,000 feet; possibly 50,000 feet or more), at the western end of the Tertiary outcrop

STATUS OF THE "GRAY STAGE" LAVAS

One of the most controversial topics of Icelandic geology concerns the status of Pjetursson's "Gray Stage" lavas. (Pjetursson, 1910). These are pale-colored and coarse-grained basalt lavas[8] which commonly cap Tertiary basalt mountains in Iceland. These lavas have long been regarded as much later in age and in some subtle way different from the main Tertiary basalt succession. In places, moraines or moraine-like deposits are interbedded with them. It is not intended here to discuss the question of the age of the "Gray Stage" rocks, which has been reviewed by several authors, for instance, by Hospers (1954). In what follows, the significance of the distinctive pale color of the lavas will alone be considered.

Pale-colored basalts of similar appearance

[8] Many of the basic lavas in Iceland, if classified strictly on their grain size, would be termed "dolerite," and in Iceland the "Gray Stage" and other late Tertiary or Quaternary lavas have, in fact, commonly been termed thus. The writer follows the more common usage of terming a basic lava "basalt," irrespective of its grain size.

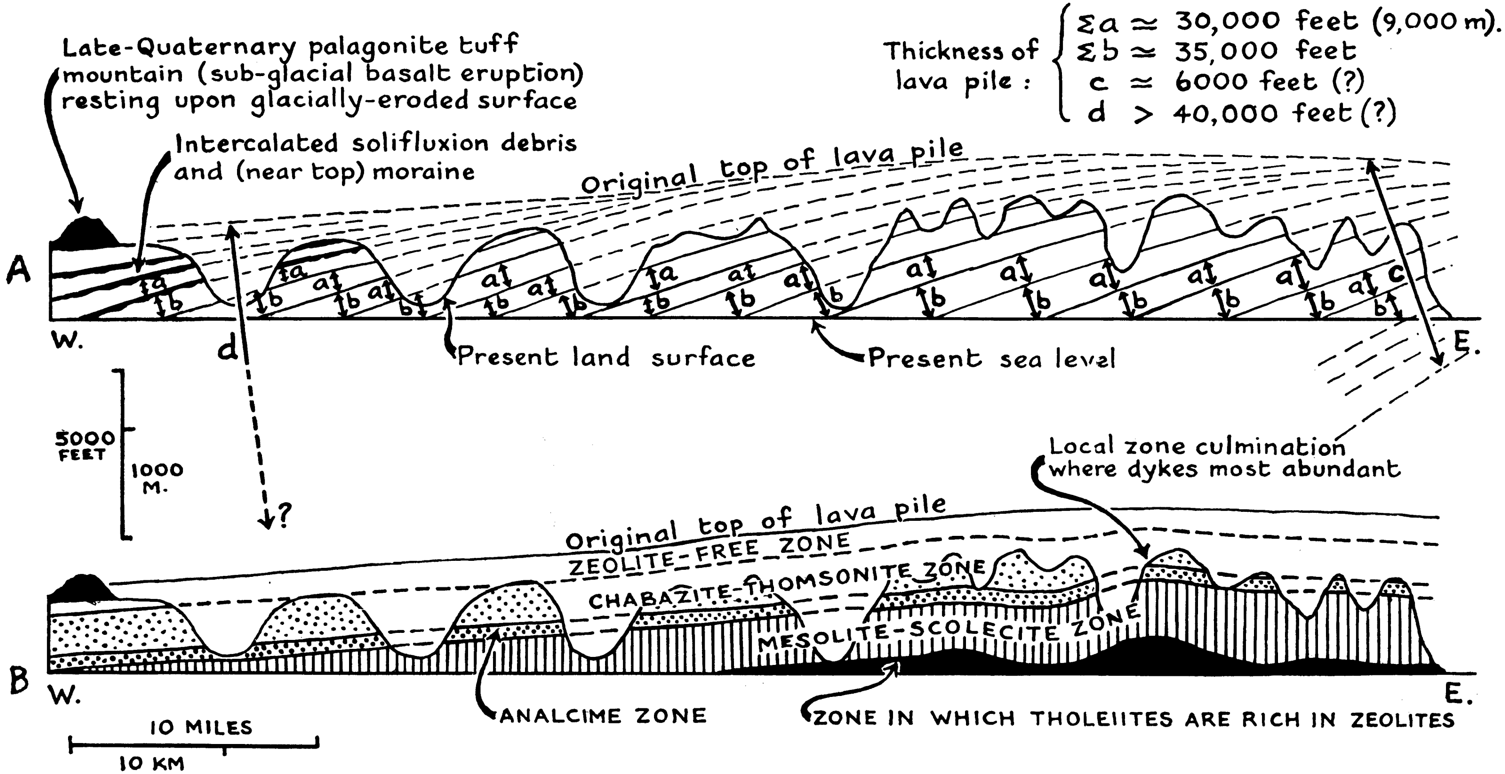

FIG. 5.—Diagrammatic sections across the Tertiary lava pile in eastern Iceland showing the inferred relationship between the original top of the pile and the lava stratigraphy (*A*) and zonal distribution of amygdale minerals (*B*). The western end of the sections corresponds to sections in upper Jökuldalur and Fljótsdalur; the eastern half corresponds to exposures in the eastern fiordlands.

to the "Gray Stage" rocks have now been found by the writer more than midway down in the Tertiary succession on a number of high mountains in eastern Iceland. It is quite clear that the pale color there marks the condition of normal and fresh olivine basalt, a condition in which certain secondary minerals are absent (because the lavas have never been sufficiently deeply buried) and which is characteristic of the upper parts of the chabazite-thomsonite zone and the succeeding zeolite-free zone. Olivine basalts are in this condition until such time as zeolitization sets in, when the color rapidly darkens in response to the development of certain secondary minerals in the rocks. Dark-colored olivine basalts in the lower zeolite zones match the pale-colored basalts in grain size, in content of the pyrogenetic minerals, and, indeed, in all respects but in their darker color and in the presence of major amounts of secondary minerals in the former and their scarcity or absence in the latter.

The "Gray Stage" lavas represent, therefore, basalt in a fresh condition and not necessarily a distinct stratigraphic unit as has often been thought to be the case. The change in color may sometimes take place at the level of a prominent sedimentary horizon in the lava pile, giving the appearance of an unconformable relationship and considerable age difference between the lavas below and above the sedimentary layer. This in no way invalidates the general conclusions expressed above. Indeed, the color change is most likely to occur at the level of a relatively impermeable sedimentary layer interposed between permeable lavas in which there is ready circulation of water; heat would tend to build up below the blanketing sedimentary layer, and the thermal gradient would be steeper in this layer than in the lavas below or above.[9]

[9] Bodvarsson (1957) records a lower thermal conductivity for an Icelandic basic tuff (0.0023 cal/sec ° C cm) than for fresh basalt (0.0039 to 0.0045 cal/sec ° C cm).

THE STRUCTURE OF ICELAND

The structure of Iceland is broadly synclinal, the axis crossing the country from the north coast to the southwest extremity. A broad belt of Quaternary volcanic rocks is encountered along this axis, and the great Tertiary lava pile is exposed in extensive outcrops on either side, generally inclined toward the central axis.

Observations by the writer at a number of points west of the central axis suggest that the relationships there are essentially a mirror-image of those in eastern Iceland, the structure being more or less symmetrical about the axis of post-Tertiary volcanicity crossing the center of the island. In the Hvalfjördur-Esja area in western Iceland, Rutten (1959) has recently demonstrated a marked thickening of the lavas in the direction of the central axis of Iceland, accounting for it by postulating two unconformities in the lava sequence.

The thickening of the lavas down-dip in Iceland, if continued beyond the limits of surface exposures, would imply the existence of an enormous thickness of lavas along the central axis; a thickness very much in excess of 30,000 feet: a thickness of geosynclinal dimensions.[10]

Tilting of the lavas must have taken place throughout the long period of volcanicity, probably due to a steady subsidence which was greatest along the central axis, where one must suppose volcanic activity to have been most intense. It is along this axial belt that volcanic activity persists at the present time.

The writer believes that subsidence, greatest in the regions of greatest thickness of lavas, is one of the characteristic features of the Tertiary basaltic region of the North Atlantic—subsidence that is consequent on the transfer of great volumes of basaltic magma from below the crust to the earth's surface.

[10] That such enormous thicknesses have not been observed lower in the geological record may be attributed to the great weight of such a pile of lavas and dikes, making it unlikely ever to be upfolded.

It is probable that the dip resulting from the unequal subsidence is greatest where the rate of increase in thickness of the lava pile is greatest. The crustal flexure along the east coast of Greenland (Wager and Deer, 1938) may be an extreme example, with steep dip due to an unusually rapid increase in thickness.

Subsidence and formation of a lava plain of low relief is considered to be more characteristic of basaltic eruptions of Icelandic type than plateau-building, and the term "plateau-lavas," so often applied in such basaltic regions, is far from satisfactory. That some areas of such lavas do form plateaus may be due more to the accidents of subsequent regional changes of level and erosional history than to the original position of the lavas, and Tyrrell's expressive term "flood basalts" (Tyrrell, 1937) is much to be preferred.

The thinning of the lavas in Iceland updip, away from the central axis of the country, if prolonged beyond the limits of exposures, would imply a thinning of the lava pile to zero only a short distance (perhaps a few tens of miles) offshore. This suggests that the Tertiary volcanic piles exposed in Iceland and perhaps in the other areas in the North Atlantic (e.g., the Faeroes and Rockall Bank; East Greenland and the adjacent Denmark Strait; and West Greenland and the sea just west of it) represent more or less separate elongated lava lenticles of exceptionally great thickness rather than eroded remnants of an original continuous lava plain stretching from the British Isles to Greenland.[11]

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[11] Recent seismic refraction studies along the Mid-Atlantic Ridge (Ewing and Ewing, 1959) suggest that the 5–6 km/sec layer, presumably volcanic rock thickens toward Iceland from about 3 km. (400 mi. SW. of Iceland) to over 4 km. (250 mi. SW. of Iceland). The Mid-Atlantic Ridge in the North Atlantic region appears to be a prolongation of the central axial belt of Iceland.

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