THE STRUCTURE OF EASTERN ICELAND

George P.L. Walker

Department of Geology,
The Imperial College of Science and Technology,
London SW7 2BP, England.

ABSTRACT. This review is based on compilations of dips, the distribution of amygdale minerals, and the intensity of the dyke swarms. These compilations enable the position of the original top of the crust to be deduced. The top lies generally well above the present summit levels, but is highest in the belt of country within which the highest summits occur. There is also a general rise southwards along the length of the belt to a maximum in the Quaternary volcanic district along the edge of the Vatnajokull. The non-parallelism of lava isochrons and dyke isochrons implies that there was a progressive southward shift in the zone of maximum spreading and probably a progressive intensification of activity as well.

1. INTRODUCTION

The Tertiary/Quaternary lava pile of eastern Iceland is inclined in a general westerly direction to expose a 10 km thickness of lava flows covering the period from approximately 15 m.y. ago [1,2,3]. Practically the entire Tertiary sequence was erupted sub-aerially: occasional hyaloclastites and pillow lavas found for example at 14°02'W, 64°50'N, and 14°39'W, 64°33½'N, were probably formed in temporary ponds, and lignite beds with overlying columnar basalt were formed in temporary depressions [4]. Pyroclastic rocks and terrigenous sediments interstratified with the lavas constitute approximately 6% of the total thickness; the former include acid ignimbrites, some of them welded [5,6].

Silicic volcanic rocks are more or less restricted to several discrete areas in which locally great thicknesses of intermediate and acid rocks occur. These discrete areas are called central

Kristjansson (ed.), Geodynamics of Iceland and the North Atlantic Area. 177-188. *All Rights Reserved.*

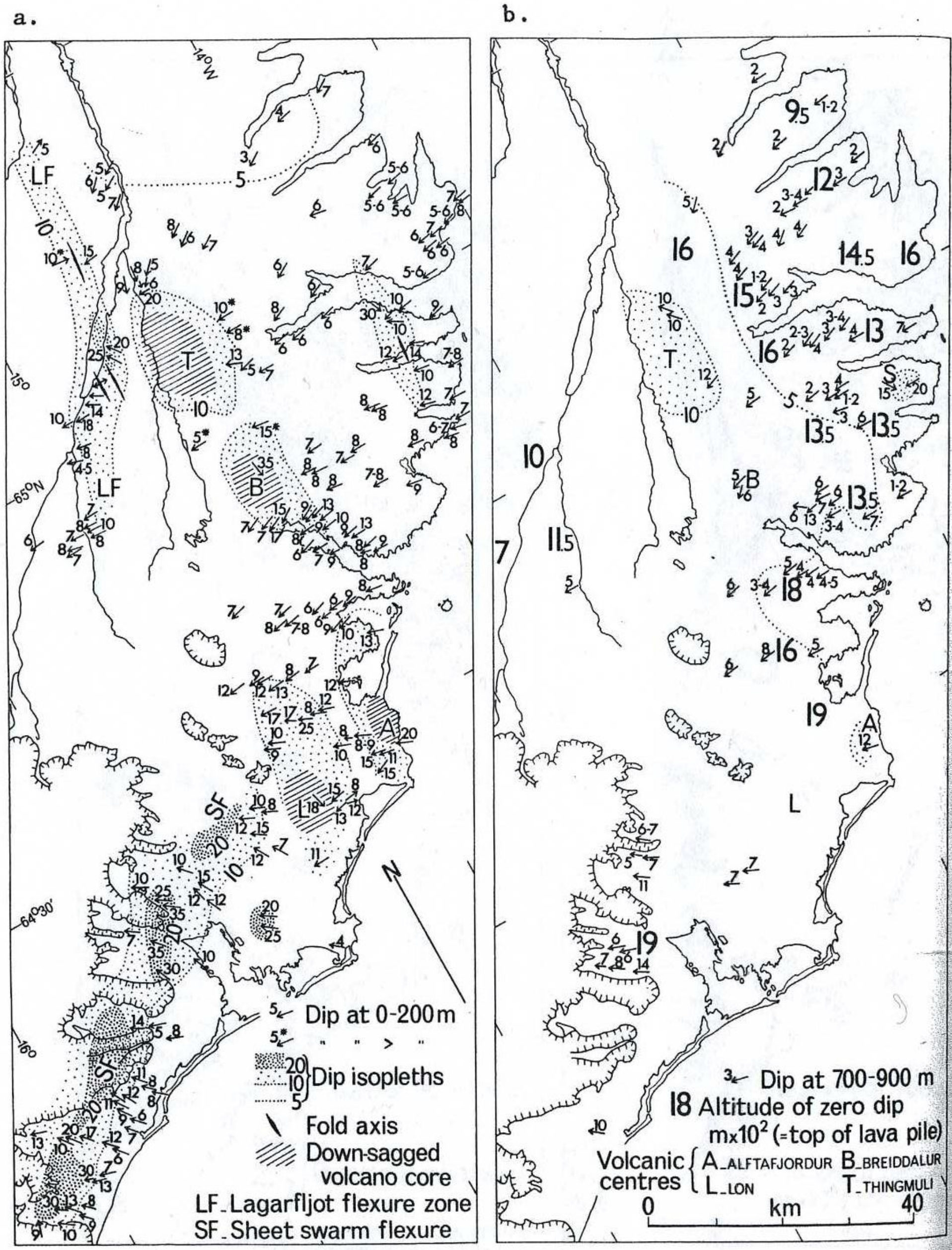

Fig. 1. The dip of the volcanic rocks in eastern Iceland, measured at two levels and contoured; b also gives the extrapolated altitude of zero dip.

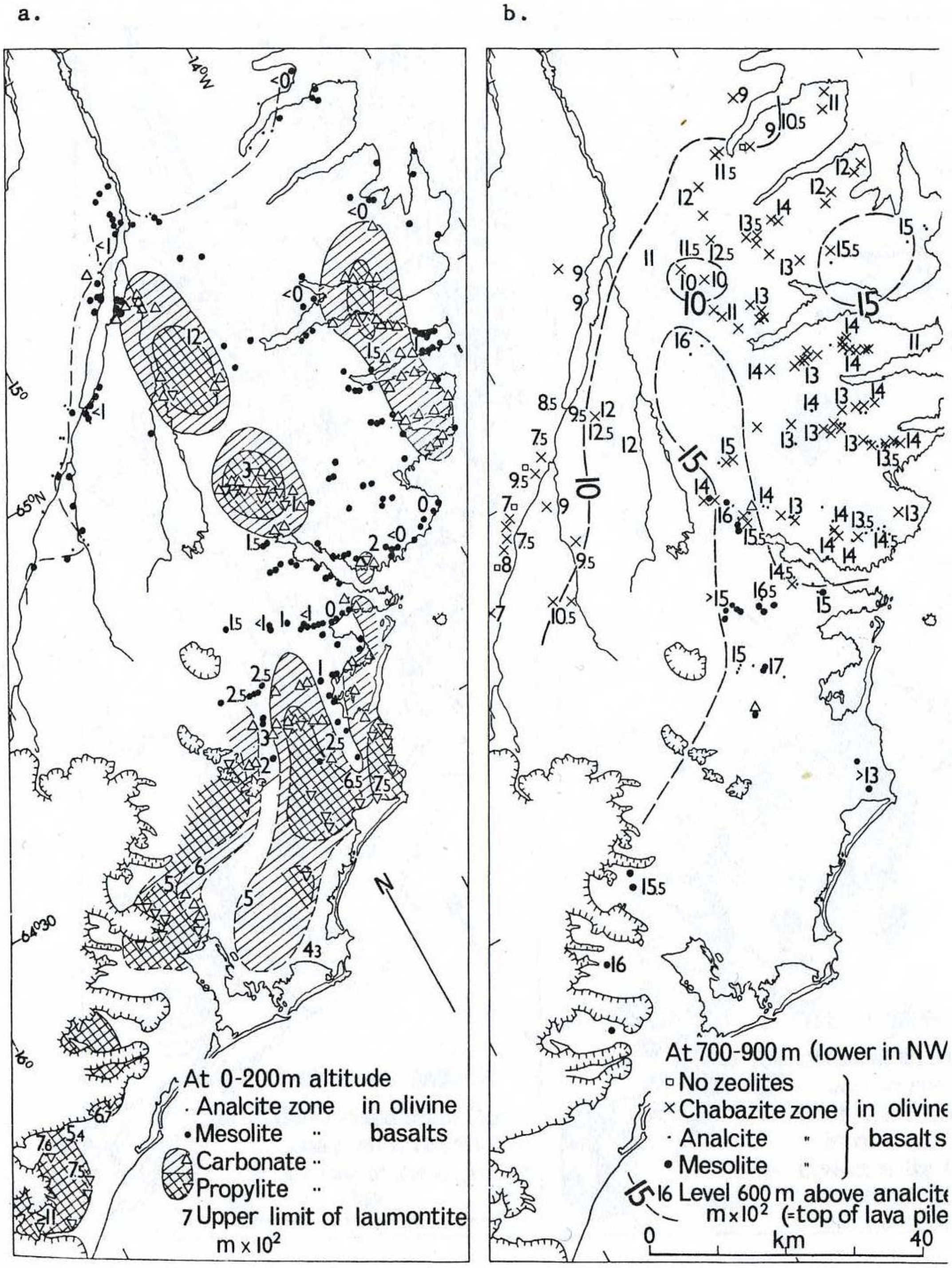

Fig. 2. The distribution of amygdale minerals at two levels in the basalts of eastern Iceland.

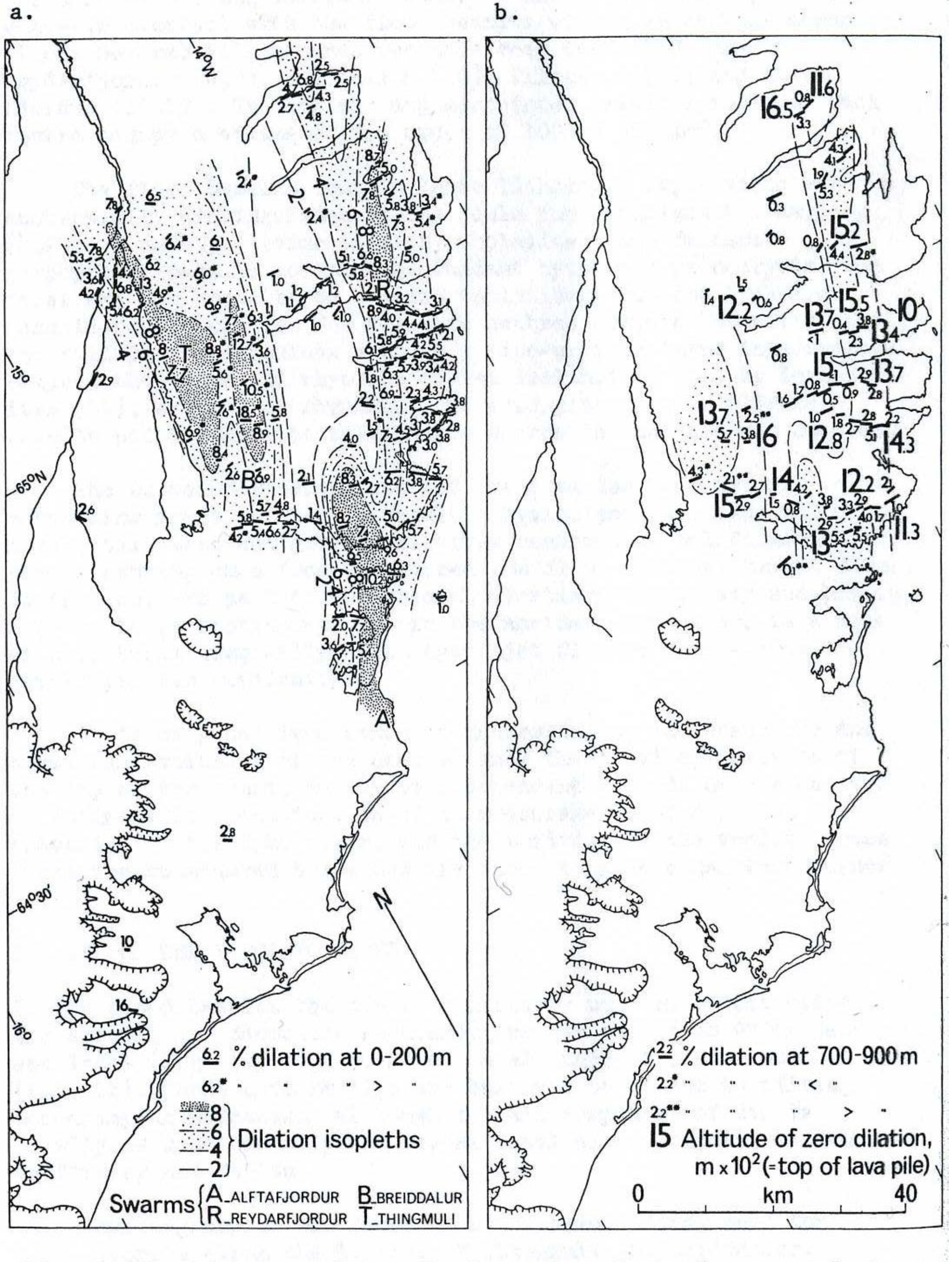

Fig. 3. The dyke swarm intensity in eastern Iceland, measured at two levels and contoured; b also gives the extrapolated altitude of zero intensity.

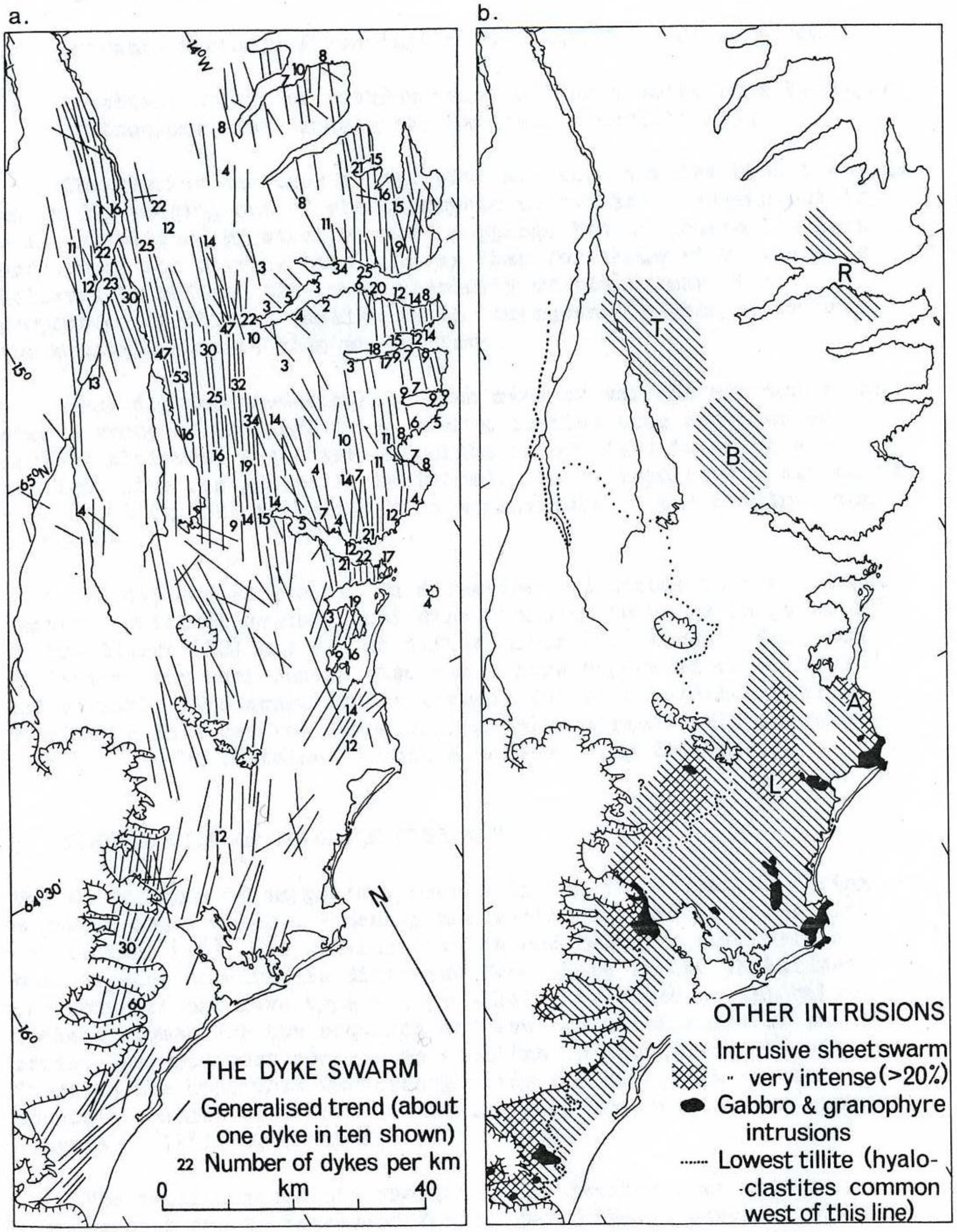

Fig. 4. The distribution of dykes and intrusive sheets in eastern Iceland; b also shows the known intrusions of gabbro and granophyre.

volcanoes--"silicic volcanic centre" would be more appropriate for some--in contrast with the flood basalts within which they occur [7,8]. Several volcanic centres have been described, namely Reydarfjordur [4,9], Breiddalur [10], Thingmuli [11] and Alftafjordur [12,13]. The silicic and associated basaltic rocks of each centre occupy a volume of the order of 100 to 500 km^3.

The flood basalts contain three lithologic types which were successfully distinguished in the field for stratigraphic mapping [4,9,10], namely olivine basalts, tholeiites, and feldspar-porphyritic basalts containing abundant bytownite phenocrysts. The first are now known to be olivine tholeiites, but the lithologic name is retained here. The volcanic centres contain tholeiite, and the silicic rocks include extremely fine-grained lavas intermediate between tholeiite and rhyolite called icelandites [11] or icelandesites [14], as well as rhyolites and acid pitchstones. Olivine basalts and porphyritic basalts are scarce in the volcanic centres.

The Quaternary succession differs from the Tertiary in containing great volumes of basaltic hyaloclastites; also pillow lavas, tillites, and grey diamictites regarded as solifluxion sheets resting on a frost-shattered and frost-upheaved basalt floor. In the southern part of the area the Tertiary-Quaternary succession appears to be continuous, but in the northern part there is a zone of structural complexity--the Lagarfljot flexure zone--which interrupts the continuity.

It is of great importance in understanding the structure and erosional evolution of the area to know the original position of the top of the crust, and three independent methods have been used to estimate its position, based on measurements of dip, the intensity of the dyke swarm, and the position of the zeolite zones. These are considered below and are shown to give consistent values.

2. DIP OF THE VOLCANIC ROCKS

In the flood basalts the dip is remarkably uniform in direction and amount, and decreases regularly upwards from 6 to 9° or near sea level (Fig. 1a) to 2 to 6° at an altitude of 700 to 900 m (Fig. 1b). These uniform dips are believed to be due to tilting accompanying volcanism, although a small component of dip is locally no doubt an original depositional slope. Departures from uniformity are due to:

a. Down-sagging of the floor of a volcanic centre, seen for example along the E. side of Thingmuli and Breiddalur.

b. Flexuring in the intrusive sheet complex of S.E.Iceland and the sheet swarm north of the Lon centre, believed to be caused by the weight of the sheet swarms there.

c. Probable tectonic flexuring in the Lagarfljot flexure zone.

d. Localised uplift or pushing aside of the country rock by major intrusions, for example the Sandfell laccolith [15].

The regular decrease in dip with altitude implies that there is an up-dip wedging-out of stratigraphic units. This wedging-out is well established by stratigraphic mapping, but in general is less pronounced for olivine basalt lavas than for tholeiites, which is believed to reflect the lower viscosity of the former. The proportion of olivine basalts is in consequence higher at or near the mountain summits than at sea level.

Many dip measurements have been made at various altitudes, and when a group of readings taken over a limited area are plotted against altitude, a scatter of points is obtained to which a straight line can generally be fitted. The extrapolated altitude of zero dip (Fig. 1b) is believed to approximate to the original top of the crust.

The dip varies greatly in direction and amount in the volcanic centres. Original depositional dips, thought to be as large as 17° at Breiddalur [10] and 22° at Alftafjordur [12] account for some variation, but each centre also has a core region in which steep and variable dips appear to be largely due to subsidence. This subsidence is a central down-sagging which appears only occasionally [13] to be contained within a caldera ring fracture.

3. DISTRIBUTION OF AMYGDALE MINERALS

The assemblages of amygdale minerals in the flood basalts define mappable zones which are nearly horizontal and are parallel with one another [16]. The olivine basalts and feldspar porphyritic basalts have assemblages different from those in the tholeiites, but zones in one lava type are parallel with those in the other. Table 1 summarises the sequence and average thicknesses of the zones. The uppermost zone of no zeolites in the olivine basalts is found in the uppermost Quaternary rocks and also high on some mountain summits well down in the Tertiary succession, for example Skagafell (14°18'W, 65°09'N).

The zeolite zones are thought to be developed at different temperatures and to represent fossil geoisotherms parallel with the original top of the crust. This surface is believed to lie some 600 m above the top of the analcite zone, and its estimated position is given in Fig. 2b. The zeolites are in part derived from mud washed into the amygdales, and the stratified mud is seen in all stages of zeolitisation, commonly with a small dip showing that tilting of the lavas had commenced before the mud was lithified.

TABLE 1. Summary of sequence and average thicknesses of zones of amygdale minerals in the flood basalts of eastern Iceland

Zones in olivine basalt lavas	Average thickness	Zones in tholeiite lavas
zone of no zeolites	c. 150 m	
		zone of no minerals
chabazite-thomsonite	450 m	
analcite	150 m	
		mordenite-chalcedony
	300 m	
mesolite-scolecite		
	c. 600 m	zone of abundant zeolites (additional to mordenite)
laumontite zone		laumontite zone

Each volcanic centre has a propylitised core in which albite and chlorite and, in an inner zone, epidote are abundant. The rocks have a distinctive pale green colour but from a distance they often resemble rhyolites. Similar alteration is associated with the sheet complex in S.E.Iceland. Pyrite is widely disseminated, laumontite and carbonates are common, and a lime garnet also locally occurs. The propylite zone is enclosed by a carbonate zone (Fig. 2a) rich in calcite often platy on 0001, aragonite often in large masses paramorphed by calcite, and dolomite. The famous Helgustadir Iceland Spar mine (13°51'W, 65°02'N) is situated in this zone.

These propylite and carbonate zones delineate fossil high temperature geothermal fields. Each has a volume of the order of 100 km^3, extending generally to less than 700 m above sea level. These zones locally overlie flood basalts and have either a mushroom shape or are "perched" like a perched water table. Larger intrusions also have a propylite aureole [12,17].

The deepest (laumontite) zone in the flood basalts (Fig. 2a) is below sea level over most of the northern half of the area but rises to 1200 m at Thingmuli and in the extreme S.W. The top of this zone, which is on average about 1700 m deep, could be used to estimate the position of the original top of the crust, but laumontite clearly fluctuates in height and occurs also in the propylite zones where the thermal gradient may have been much higher than usual.

4. THE DYKE SWARMS

Dykes are abundant, and the dyke intensity has been measured in more than 200 well-exposed strips of country totalling more than 250 km long; these strips contain 2700 dykes totalling 11 km wide. The intensity is given in Fig. 3 as the percentage of rock made up by basic dykes, and Fig. 4a as the number of dykes per km. There are several swarms, one for each volcanic centre, in which the maximum sea level intensity exceeds 8%.

The dyke intensity everywhere falls with altitude, and when intensity values measured over a limited area are plotted against altitude, a scatter of points is obtained to which a straight line can generally be fitted. The extrapolated altitude of zero intensity (Fig. 3b) is believed to approximate to the original top of the crust.

5. INTRUSIVE SHEET SWARMS

Intrusive sheets, mostly basic and averaging less than 1 m thick, occur as swarms containing thousands of members in several areas. They and their origin are discussed elsewhere([19] and the following paper of this volume). The intrusive sheet complex in the deeply eroded Quaternary hyaloclastite belt along the edge of the Vatnajokull (Fig. 4b) is particularly intense and in places (e.g. at 16°11'W, 64°09$\frac{1}{2}$'N) sheets constitute about 100% of the rock. The sheets dip in the same direction as, although more steeply than, the rocks they cut. Each volcanic centre also has a swarm of sheets, preferably not called cone sheets [19], emplaced mainly in the acid volcanic rocks.

The stratification shown by chalcedony ("onyx") filling amygdales in the flood tholeiites is normally horizontal. However in the flexured basalts associated with the intrusive sheet swarms it is sometimes not horizontal (Fig. 5). Tilting of these basalts is attributed to subsidence caused partly by the weight of the lavas and partly by the weight of intrusive sheets. It is thought that tilting by the former takes place while the lavas involved are within 10 or 20 km of the spreading zone and ends when no more lavas are added above. The formation of zeolites and chalcedony proceeds rapidly under this full cover. A further tilting may then take place if sheets continue to be emplaced.

6. BROAD RELATIONSHIPS

Two kinds of relationships are discussed here. The first concerns the position of the original top of the crust, and the second concerns the non-parallelism of strike lines and dyke trends. The three independent methods used to estimate the position of the first give closely comparable results, normally not differing by more than about 200 m as is evident from a comparison of Figs. 1b, 2b and 3b, which tends to confirm the broad validity of the methods.

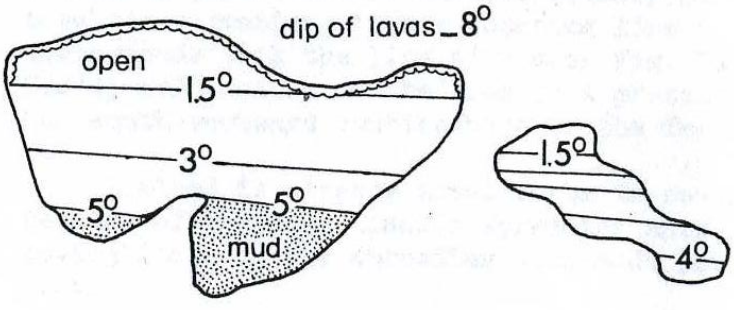

Fig.5. Variation in dip during deposition recorded by bedded chalcedony in amygdales seen at 15°36'W, 64°23'N.

A belt of high summits runs the length of eastern Iceland, ranging in height from 1150 m in the extreme N.E. to 1400 m at the edge of the Vatnajokull in the S.W. A thickness of rocks ranging from 0 m in the extreme N.E. to about 500 m in the S.W. has been eroded from above them. Both original top and summit level fall northwestwards in the vicinity of the Lagarfljot flexure zone--there is evidence that the zeolite zones are downflexed here--and there is a less clear fall eastwards from the belt of maxima.

The second relationship is a more significant one and stems from the fact that strike lines (isochrons) for the lavas at sea level from Fig. 1a are not parallel with the predominant trend of the dykes which cut them (dyke "isochrons"): the latter consistently make an angle of about 30° (measured clockwise) with the former, (Fig. 6). Only a small part of this discrepancy can be accounted for by variations in the depth of erosion.

The generally nearly constant width of each submarine magnetic strip anomaly indicates that the spreading rate is nearly constant along the length of the spreading axis. The non-parallelism of isochrons for lavas and dykes in eastern Iceland however appears to be most readily explained as resulting from magmatism being concentrated along a short length of axis, this "locus" migrating southwards at the rate of about 10 km per m.y.

Fig. 7 illustrates the position of lava and dyke isochrons at a given erosion level for a number of situations in all of which the spreading axis is fixed in position. In b and c the locus is fixed in position, but in c the spreading rate accelerates with time. In d and e the locus moves and in e the spreading rate accelerates with time. Other possibilities also exist.

The situation in eastern Iceland is similar to that of either

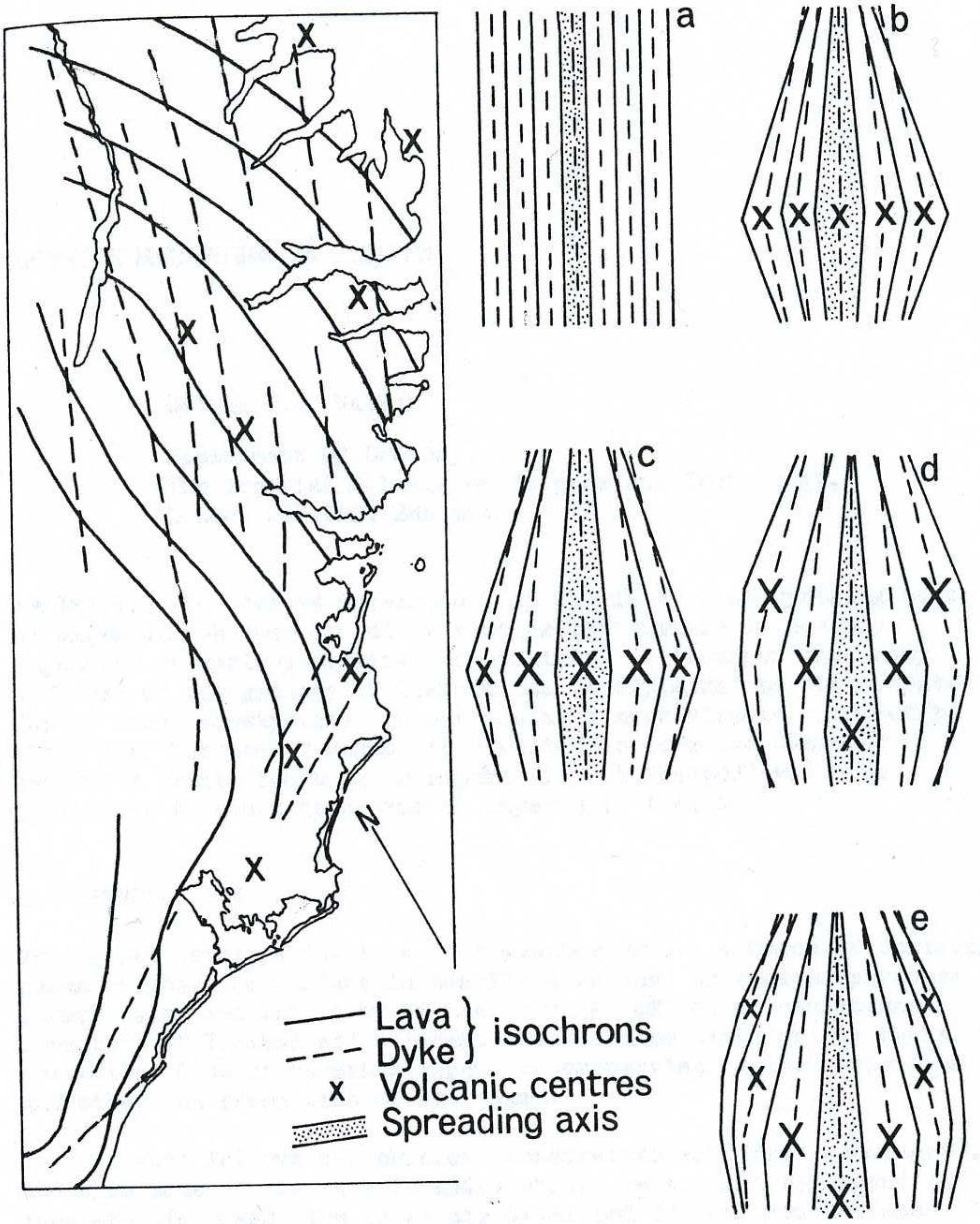

Fig. 6 (left). Isochrons for lavas and dykes in eastern Iceland showing their consistent non-parallelism. x's mark volcanic centres.

Fig. 7 (right). Distribution of lava and dyke isochrons for five different spreading axis situations.

d or e; the author tends to favour the second alternative, but a choice can only be made by closer dating of the rocks involved. The progressive south-westwards migration of acidic volcanic centres [8] supports the idea of a moving locus; if, as is suggested in the following paper, acidic centres develop at loci of most intense basaltic magmatism, then a younging line of acidic centres corresponds with the line of x's on Fig. 7d and e. The active Torfajokull acidic centre lies on a present spreading axis at the south-westward continuation of the Tertiary line.

Iceland is already known to be in several ways an anomalous section of the mid-Atlantic spreading axis, and this postulated moving locus on the spreading axis adds yet another anomaly to the list.

REFERENCES

1. N. H. Gale, S. Moorbath, J. Simons and G. P. L. Walker, *Earth Planet. Sci. Lett.*, *1*, 284, 1966.
2. S. Moorbath, H. Sigurdsson and R. Goodwin, *Earth Planet. Sci. Lett.*, *4*, 197, 1968.
3. P. Dagley and others, *Nature*, **216**, 25, 1967.
4. I. L. Gibson, D. J. J. Kinsman and G. P. L. Walker, *Greinar* **4**, (2), Soc. Sci. Islandica, Reykjavik, 1966.
5. T. Tryggvason and D. E. White, *Am. J. Sci.*, **253**, 26, 1955.
6. G. P. L. Walker, *Quart. J. Geol. Soc. Lond.*, **118**, 275, 1962.
7. G. P. L. Walker, *Bull. Volcanol.*, **27**, 1, 1964.
8. G. P. L. Walker, *Bull. Volcanol.*, **29**, 375, 1966.
9. G. P. L. Walker, *Quart. J. Geol. Soc. Lond.*, **114**, 367, 1959.
10. G. P. L. Walker, *Quart. J. Geol. Soc. Lond.*, **119**, 29, 1963.
11. I. S. E. Carmichael, *J. Petrol*, **5**, 435, 1964.
12. D. H. Blake, *Sci. in Iceland*, **2**, 43, 1970.
13. D. H. Blake, *Geol. Mag.*, **106**, 531, 1969.
14. K. Grönvold, *Structural and petrochemical studies in the Kerlingafjöll region, Central Iceland*. D. Phil. thesis, Oxford University, 1972.
15. L. Hawkes and H. K. Hawkes, *Quart. J. Geol. Soc. Lond.*, **89**, 379, 1933.
16. G. P. L. Walker, *J. Geol.*, **68**, 515, 1960.
17. R. W. Johnson, *Sci. in Iceland*. Anniv. vol, 55, 1968.
18. G. P. L. Walker, *J. Geol. Soc. Lond.*, **130**, (in press), 1974.