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Extensional tectonics of southwest Iceland

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Key words. – Iceland, Mid-Atlantic rift, Paleo-stress fields, Faults, Dykes, Inclined sheets, Joints.

Abstract. – The main extensional structures of southwest Iceland are normal faults, dykes, inclined sheets, mineral veins and joints. These occur in host rocks that range in age from Holocene to Pliocene. The normal faults are vertical at the surface in the Holocene rift zone and range in length from 360 m to 9 km and in throw from 0.5 to 40 m. In the Pliocene-Pleistocene fault swarms the fault dip is 53-89° and the throw is 0.5-150 m, with 90 % of the faults having throws of less than 10 m. The mean dip of 473 regional Pleistocene dykes is 69°, that of 14 Pliocene dykes is 70° and the average thicknesses are 1.4 m and 1.6 m, respectively. The crustal dilation due to dykes and normal faults is generally in the range 1-6 %. In addition to the regional dyke swarm, there are two local swarms of inclined sheets. The sheets in each swarm dip towards a common centre, presumably a shallow crustal magma chamber associated with a central volcano. The dip distribution shows two peaks, one corresponding to shallowly dipping sheets, the other to steeply dipping sheets. The sheets range in thickness from 0.1 m to 10 m.

The paleostress tensor was determined using fault-slip data from several sites in southwest Iceland. The results indicate that the minimum compressive stress axis (σ_3) is subhorizontal and trends mostly N110-130°E. This conclusion is supported by the NE trend of all major structural elements in this area. At a few sites the reconstructed stress tensor had σ_3 trending N140-150°E, but most of these sites are in the vicinity of extinct shallow magma chambers, or major dykes, where the local stress field disturbed the regional stress field associated with rifting.

The results obtained in this study indicate that the process of crustal spreading in southwest Iceland occurs in several steps. Most faults and dykes develop within the active rift zone in a direction that is perpendicular to the time-averaged regional direction of σ_3. In the vicinity of shallow magma chambers local stress fields are generated where σ_3 trends differentely from that of the regional stress field, and these fields control the emplacement of inclined sheets. Short-term local stress fields associated with dyke emplacement may also give rise to strike-slip or reverse movement on already formed normal faults. Some faults and joints may be formed, or reactivated, outside the rift zone, or at its margins, in a stress field where σ_3 trends essentially parallel to the rift zone. This stress field is attributed to the lateral loading of the crust in the rift zone, as a consequence of dyke emplacement. The NW trending faults and joints, and some fjords and valleys, are likely to be generated in this stress field.

Tectonique en extension du Sud-Ouest de l'Islande

Mots clés. – Islande, Rift medio-atlantique, Paléo-champs de contraintes, Failles, Dykes, Filons volcaniques, Joints.

Résumé. – Dans les terrains d'âge holocène à pliocène du Sud-Ouest de l'Islande, les principales structures extensives sont : des failles normales, des dykes, des filons volcaniques, des veines minérales et des joints. Les failles normales, subverticales à la surface dans la zone de rift holocène, ont des longueurs de 360 m à 9 km et des rejets de 0,5 à 40 m. Dans les terrains d'âge plio-pléistocène, les pendages des failles varient de 53 à 89° et les rejets de 0,5 à 150 m, ces derniers sont cependant inférieurs à 10 m dans 90 % des cas. Le plongement moyen de 473 dykes pléistocènes est de 69°, celui de 14 dykes pliocènes est de 70° et leurs épaisseurs moyennes sont de 1,4 à 1,6 m, respectivement. La dilatation crustale attribuable aux dykes et aux failles normales est généralement de l'ordre de 1 à 6 %. En plus du faisceau de dykes régional, il existe dans ce secteur deux faisceaux locaux de filons volcaniques inclinés, plongeant vers un point commun : probablement une chambre magmatique peu profonde associée à un centre volcanique. La distribution des inclinaisons montre deux pics, l'un correspondant à des filons peu inclinés, l'autre à des filons fortement inclinés. L'épaisseur de ces filons varie entre 0,1 et 10 m.

Les paléo-états de contraintes ont été construits à partir de l'analyse des systèmes de failles et de micro-failles striées dans plusieurs sites du Sud-Ouest de l'Islande. Les résultats des calculs indiquent une contrainte principale minimale ($\sigma3$) subhorizontale et d'azimut N110-130°. Ceci est corroboré par la direction NE-SW de tous les éléments structuraux majeurs d'échelle régionale.

Dans quelques sites, l'axe $\sigma3$ est orienté N140°-150°, mais la plupart de ceux-ci sont situés à proximité de chambres magmatiques, peu profondes, éteintes ou de dykes majeurs, là où des champs de contrainte locaux perturbent le champ de contrainte régional associé au rifting.

Les résultats obtenus dans cette étude indiquent que, dans le processus d'expansion crustale du Sud-Ouest de l'Islande, plusieurs stades peuvent être distingués en termes de paléocontraintes. La plupart des failles et des dykes se sont formés dans une zone de rift actif dont la direction est perpendiculaire à la direction régionale moyenne de $\sigma3$. A proximité des chambres magmatiques peu profondes, des champs de contrainte locaux se sont développés, contrôlant l'emplacement de filons volcaniques inclinés. Des états de contrainte locaux associés à la présence de dykes ont pu également produire des mouvements décrochants ou inverses sur des failles normales déjà existantes. Quelques failles et joints peuvent s'être formés ou avoir été réactivés en dehors de la zone de rift ou sur ses marges dans un état de contrainte caractérisé par un axe $\sigma3$ pratiquement parallèle à la zone de rift. Cet état de contrainte est attribué à un confinement latéral de la croûte, dans la zone de rift, dû à l'injection des dykes. Les failles et les dykes de direction NW-SE, de même que certains fjords et vallées, sont probablement dus à une formation dans un tel état de contrainte.

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I. – Introduction

The geology of southwest Iceland offers an excellent opportunity for studying extensional tectonics at divergent plate boundaries. Less than 10 km from the Holocene rift zone, there are deep valleys and fjords dissecting the corresponding Pleistocene and Pliocene fault and dyke swarms (fig. 1). The data from these older swarms can be used to infer the infrastructure of the nearby Holocene fissure swarms and to test models on the mechanism of crustal extension.

The principal aim of this paper is to describe the extensional structures of southwest Iceland. We present detailed data on dykes, inclined sheets, faults, mineral veins and slickensides from which we infer the regional stress field in this part of Iceland. A second aim is to relate these data to the general geodynamic framework of divergent plate boundaries.

II. – Geological setting

The Holocene rift zone in southwest Iceland is the onshore continuation of the Reykjanes Ridge. It consists of specific fissure swarms, which in this part of Iceland are 7-11 km wide and 41-78 km long [Gudmundsson, 1986]. The fissure swarms are most conspicuous in the basaltic pahoehoe lava flows from the early part of the Holocene. Each swarm contains hundreds of tension fractures, normal faults (fig. 2), and volcanic fissures. The swarms outline specific volcanic systems [Jakobsson, 1979], where most of the volcano-tectonic activity takes place. As our data confirm, the volcanic systems are the surface expression of dyke and fault swarms at deeper levels in the crust.

The Pliocene area of southwest Iceland consists mainly of basaltic lava flows with occasional interbedded layers of basaltic breccias. The regional dip of the lava pile is 2-8°SE. The proportion of basaltic breccias increases towards the rift zone and is high in the Pleistocene area where, in addition, layers of tillite are common. The extensional structures of this area include dykes and normal faults [Forslund and Gudmundsson, 1991] as well as mineral veins and joints [Jefferis and Voight, 1981].

III. – Fracture patterns

Normal faults and dykes are the most common major extensional structures in southwest Iceland (fig. 3). The strike distributions of faults and dykes are similar (fig. 4), indicating that they were generated in the same stress field. The cross-cutting relationships suggest that most of the dykes are pure extension fractures. Field evidence indicates that the normal faults were formed in a direction essentially perpendicular to the direction of σ_3.

A) Normal faults

In the Holocene fissure swarms of the Reykjanes Peninsula [Gudmundsson, 1987a] and the Thingvellir area [Gudmundsson, 1987b], the normal faults are vertical at the surface (fig. 2). The general fault strike is NE and subparallel with the trend of the associated fissure swarms. The measured throw on the faults in the Holocene lava flows is 0.5-40 m, the length is 0.36-9 km, and the width is 0-68 m. Most fractures in the fissure swarms, however, are not normal faults but tension (mode I) fractures. On average, the tension fractures are much shorter than the normal faults and it is clear that many normal faults develop by coalescence of several shorter tension fractures. As the normal faults become longer, the maximum throw normally increases. For faults located within a single lava flow, the linear correlation coefficient between length and maximum throw ranges from 0.64 to 0.97.

In the Pliocene-Pleistocene fault swarms, most normal faults are steeply dipping (fig. 3a). The dip ranges from 53° to 89° with an arithmetic mean of 75° [Forslund and Gudmundsson, 1991]. The number of faults dipping to the east, i.e., towards the rift zone, is similar to that dipping to the west and away from the rift zone. The general strike of the faults is NE, slightly more eastward than that of the faults in the nearby Thingvellir fissure swarm (fig. 4). In the Tertiary area of Akrafjall (fig. 1) there is, however, no dominant strike direction. The throw of the 34 Akrafjall faults ranges from 0.5 m to 48 m, but (with one exception) only those faults that strike approximately NE developed throws in excess of 7 m. Most of the faults appear to be pure dip-slip, but strike-slip movement has evidently occurred along some faults. Two faults appear to be reverse faults. One (N40°E, 61°NW, with a throw of 3.5 m) occurs in a Pleistocene area, the other (N80°E, 77°N, with a throw of 5 m) in the Tertiary area of Akrafjall.

The measured throw of the Pliocene-Pleistocene faults ranges from 0.5 m to 150 m. The mean throw of 206 Pleistocene faults is about 10 m and 90 % have throws of less than 20 m. The mean throw of 34 Tertiary faults is about 9 m. Fault breccia is common and there is a clear correlation between the throw of the Pliocene-Pleistocene faults and the thickness of the associated breccia. The breccia thickness ranges from 0.05 m to 2 m, and the linear correlation coefficient for throw and maximum breccia thickness is 0.78. This indicates that some 60 % of the variation in breccia thickness can be explained by variation in fault throw. Many faults were followed upwards in the lava pile in order to observe changes in the throw. With one exception, the throw on individual faults, measured at an altitude difference of as much as 150 m, was the same, suggesting that growth faults are rare in the exposed Pliocene-Pleistocene lava pile in southwest Iceland.

D) Dykes

Dykes in Iceland occur in two distinct types of swarms; regional dyke swarms and local sheet swarms [Gudmundsson, 1990a]. Both types of swarms are found in southwest Iceland. A local swarm of inclined (cone) sheets is associated with the Hvalfjordur central volcano, which occupies the inner part of, and the mountains north of, the fjord Hvalfjordur. Another sheet swarm, described in detail below, occurs in the Esja area (fig. 1). Many dykes of the Pleistocene area, and all dykes of the Tertiary area, are regional dykes (fig. 3b), but some were probably injected laterally from the nearby central volcanoes.

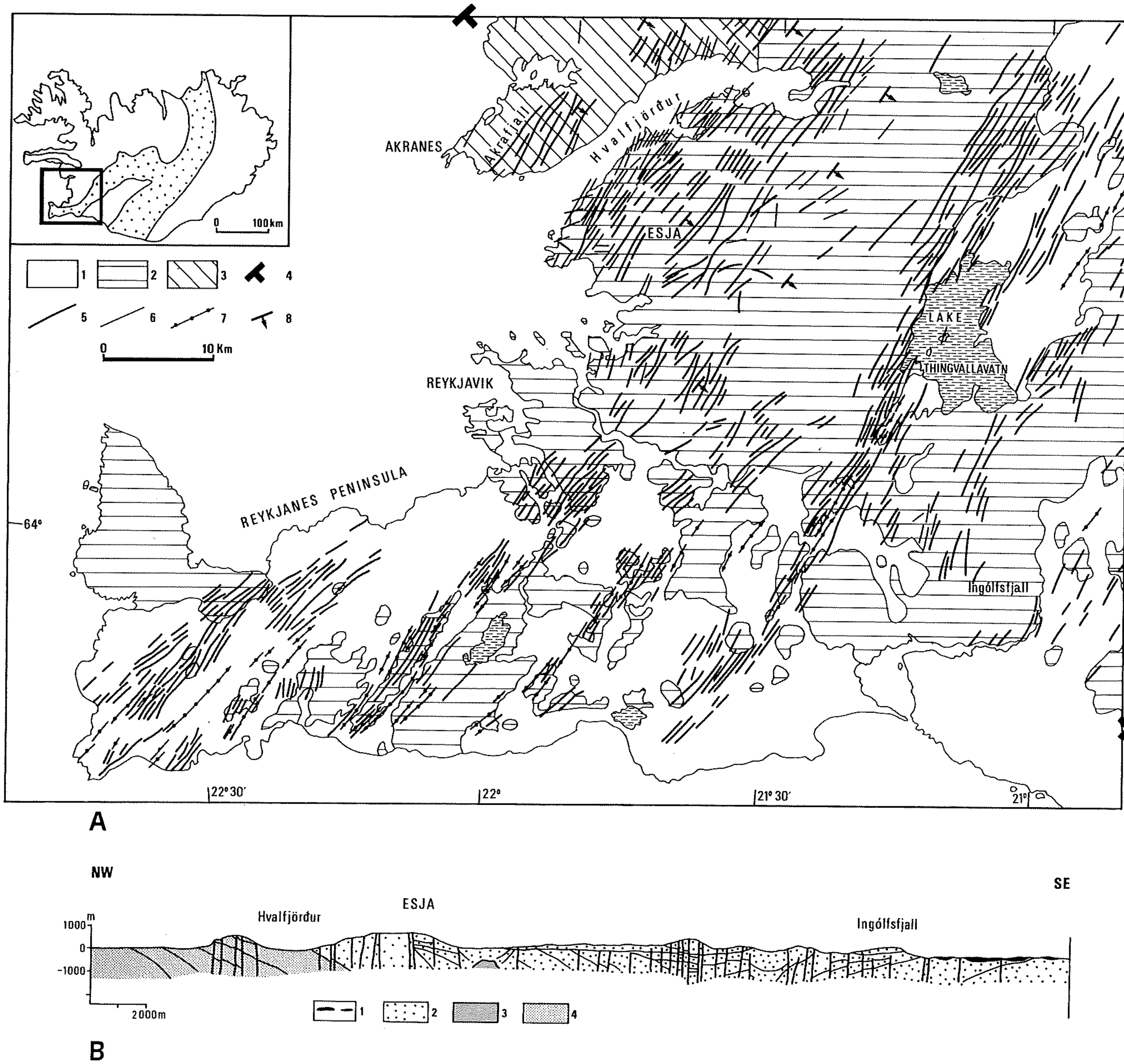

FIG. 1. – Structural map (A) and a cross-section (B) of southwest Iceland. Modified from Saemundsson & Einarsson [1980].
A. – 1 : postglacial basaltic and andesitic lavas; 2 : late Pliocene and Pleistocene basalt (younger than 3.1 Ma) including andesite, hyaloclastite and tuffaceous sediments; 3 : Pliocene basalt (older than 3.1 Ma) including andesite and hyaloclastite; 4 : location of the cross-section B; 5 : fault or fissure; 6 : basaltic dyke; 7 : postglacial eruptive fissure; 8 : strike and dip of the lavas.
B. – 1 : postglacial basaltic and andesitic lavas; 2 : late Pliocene and Pleistocene basalt including andesite, hyaloclastite and sediments; 3 : intrusive dolerite; 4 : Pliocene basalt including andesite and hyaloclastite.

FIG. 1. – *Carte structurale* (A) *et coupe* (B) *du Sud-Ouest de l'Islande, modifiées d'après Saemundsson et Einarsson [1980].*
A. – 1 : *laves basaltiques et andésitiques post-glaciaires;* 2 : *basaltes d'âges pliocène supérieur et pléistocène (plus jeunes que 3,1 Ma), andésites, hyaloclastites et sédiments tuffacés;* 3 : *basaltes pliocènes (plus vieux que 3,1 Ma), andésites et hyaloclastites;* 4 : *emplacement de la coupe B;* 5 : *faille ou fissure;* 6 : *dyke basaltique;* 7 : *fissure éruptive post-glaciaire;* 8 : *direction et plongement des couches de laves.*
B. – 1 : *laves basaltiques et andésitiques post-glaciaires;* 2 : *basaltes d'âges pliocène supérieur et pléistocène, andésites, hyaloclastites et sédiments;* 3 : *dolérites intrusives;* 4 : *basaltes pliocènes, andésites et hyaloclastites.*

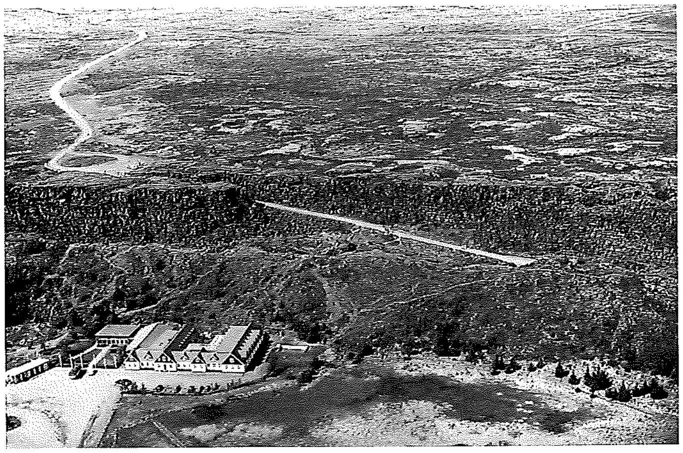

FIG. 2. – Aerial view of a vertical normal fault in a basaltic (pahoehoe) lava flow of the Holocene rift zone in southwest Iceland. The throw is 25-30 m, and the width (the separation of the fault walls) is as much as 40 m, in the middle right part of the picture.

FIG. 2. – *Vue aérienne d'une faille normale sub-verticale dans une coulée de laves basaltiques (pahoehoe) de la zone de rift holocène dans le sud-ouest de l'Islande. Le rejet de la faille est de 25-30 m et sa largeur (distance entre les deux murs) peut atteindre 40 m (partie centrale droite de la photographie).*

The mean dip of 473 regional Pleistocene dykes is 69°, the mean thickness is about 1.4 m, and the general strike is NE. The average dip is lower, and the average thickness less, than that of the regional Tertiary dykes [Gudmundsson, 1990a]. The thinness of the Pleistocene dykes can be attributed to their inferred shortness, and the low magmatic overpressure at the time of their formation, compared with the regional Tertiary dykes [Forslund and Gudmundsson, 1991]. The lower dip may reflect the influence of the local stress fields associated with the nearby crustal magma chambers.

In the Tertiary area of Akrafjall in southwest Iceland, dykes are very rare. In a 5.6 km-long profile, only 14 dykes were found. The mean values for these dykes are 25° for strike, 70° for dip, and 1.6 m for thickness. These regional dykes are thus, as regards dip and thickness, more similar to the nearby Pleistocene dykes than to the regional dykes of the Tertiary areas of east and northwest Iceland [Gudmundsson, 1990a]. This suggests that during Pliocene essentially the same factors contributed to the thinness and low dips of the dykes in southwest Iceland as those during Pleistocene.

The crustal dilation due to dykes and faults has been estimated in many profiles, with a combined length of nearly 40 km. In 3.7-9.0 km long-profiles in the Pleistocene area, the crustal dilation attributable to dykes only is 0.4-3.7 %, that attributable to normal faults only is 0.6-5.3 %, and the combined dilation attributable to both dykes and faults is 1-6.4 %. The crustal dilation due to dykes in the 5.6 km-long profile in the Tertiary area of Akrafjall is 0.4 %, that due to faults is 1.6 %, and the combined dilation is 2 %.

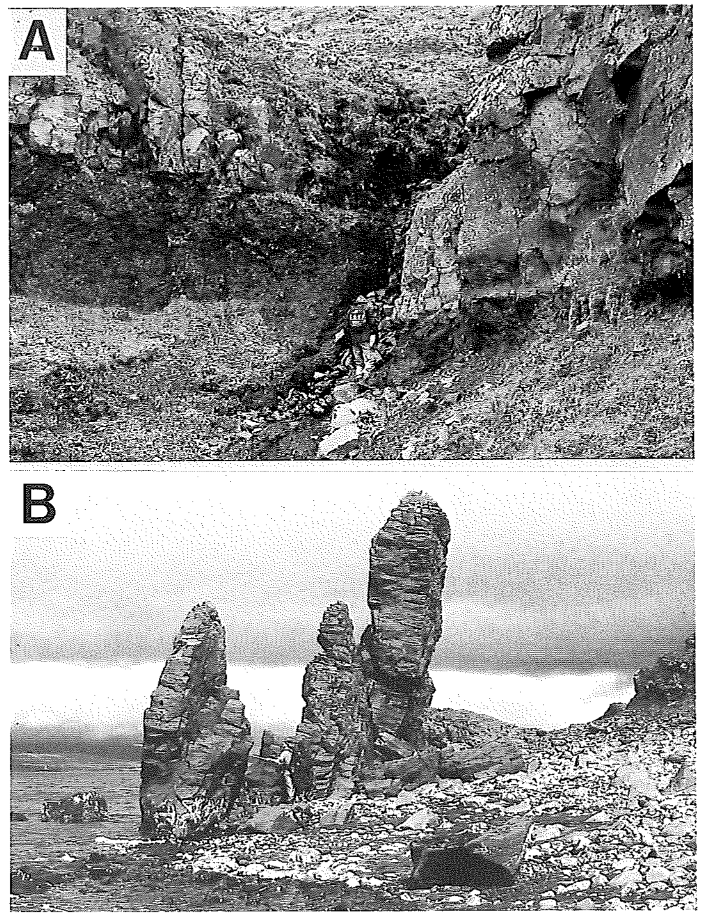

FIG. 3. – Major extensional structures of southwest Iceland.
A. – Normal fault in the Pleistocene lava pile. The fault strikes N027°E, dips 81°E, and has a throw of 4 m. A 10 cm thick breccia is associated with this fault.
B. – Basaltic dyke, striking N030°E, on the south coast of the fjord Hvalfjordur (fig. 1). The dyke dips 82°W and its thickness is 3 m.

FIG. 3. – *Structures extensives majeures du sud-ouest de l'Islande.*
A. – *Faille normale dans les couches de laves pléistocènes : azimut 27°, pendage 81°E, rejet 4 m. Une brèche de faille de 10 cm d'épaisseur est associée au plan de faille.*
B. – *Dyke basaltique d'azimut 30° sur la côte sud du fjord Hvalfjordur (cf. localisation fig. 1) : inclinaison 82°W, épaisseur 3 m.*

C) Inclined sheets of the Esja region

In order to reconstruct the local paleostress field associated with an extinct magma chamber, more than 400 inclined (cone) sheets were measured on the coast of the Esja area (fig. 1). These sheets were injected from the shallow magma chamber associated with the Kjalarnes central volcano that was active 2.8-2.2 Ma ago [Fridleifsson, 1977]. The sheets range in thickness from 0.1 m to 10 m.

The inclined sheets belong to two main sets (fig. 5a). One set consists of subvertical or steeply dipping sheets the other of subhorizontal or gently dipping sheets. The dominant strike is NNE, parallel to the trend of the present

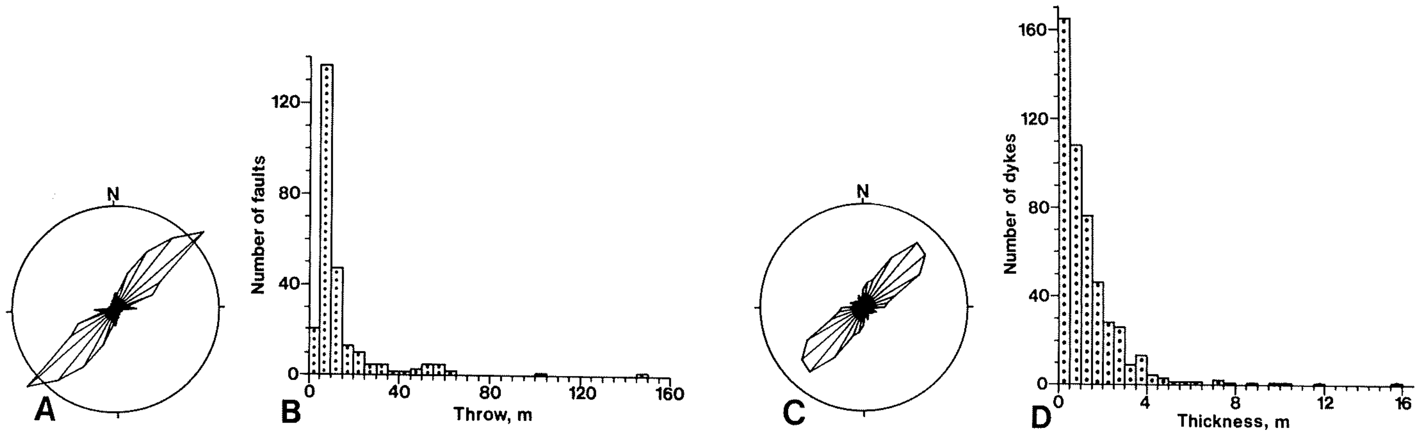

FIG. 4. – Structural data on normal faults and dykes in the Pliocene and Pleistocene areas of southwest Iceland.
A. – Rose diagram of strikes, 220 faults. Radius of the circle : 10 % of the total number of faults.
B. – Throw distribution of 240 faults. Two throws exceed 100 m (maximum : 150 m). Minimum measured throw : 0.5 m. Average throw : 9.1 m.
C. – Rose diagram of strikes, 486 basaltic dykes. Radius of circle : 10 % of the total number.
D. – Thickness distribution, 489 dykes. Average dyke thickness : 1.4 m.

FIG. 4. – *Données statistiques sur les failles (A et B) et les dykes (C et D) dans les secteurs pliocène et pléistocène du sud-ouest de l'Islande.*
A. – *Rosace des directions des failles normales (220) ; le rayon du cercle correspond à 10 % du nombre total de failles.*
B. – *Histogramme des rejets des failles normales (240) ; deux rejets sont supérieurs à 100 m, le plus important étant 150 m, la plus faible mesure est de 0,5 m ; le rejet moyen est de 9,1 m.*
C. – *Rosace des directions des dykes basaltiques (486) ; le rayon du cercle correspond à 10 % du nombre total de dykes.*
D. – *Histogramme des épaisseurs des dykes (489) ; l'épaisseur moyenne est de 1,4 m.*

rift zone in southwest Iceland and also parallel to the dominating strike of structural elements in southwest Iceland in general (fig. 1). About 20 % of the sheets, however, strike in all directions and have variable dips.

We suggest that the main sheet set (NNE trends and steep dips) reflects the effect of the regional stress field associated with the rift zone. The regional stress field would commonly dominate near the surface, in particular if the

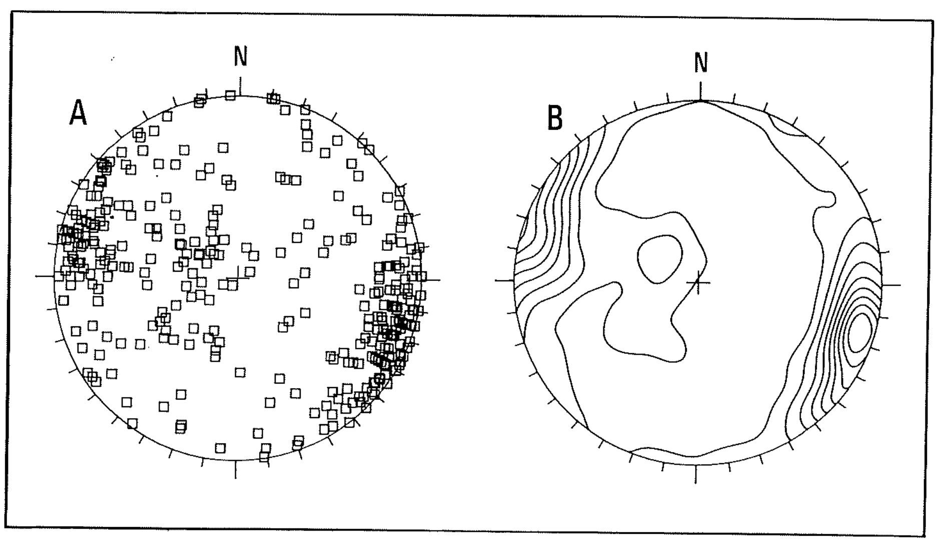

FIG. 5. – Orientation distribution of inclined sheets of the Esja region. Lower hemisphere equal area stereographic projections.
A. – Poles to sheets.
B. – Curves of equal extension (10-90 %) due to sheet thickness. Same data as in A.

FIG. 5. – *Données statistiques sur les filons volcaniques de l'Esja.*
A. – *Pôles des filons (projection de Schmidt, hémisphère inférieur).*
B. – *Courbes d'égal étirement (10-90°).*

shallow chamber was sill-like [Gautneb *et al.*, 1989]. The steeply dipping sheets, which would normally be most affected by the stress field associated with the rift zone, have a stronger NE trend than the shallowly dipping sheets, which supports this conclusion. The large-scale mechanical properties are essentially uniform throughout the lava pile. We therefore attribute the variable trends and shallow dips of the sheets in the other set primarily to the effect of the local stress field generated in the vicinity of the shallow magma chamber [Anderson, 1936; Gautneb *et al.*, 1989].

From the orientation (fig. 5A) and thickness of each sheet, a 3D estimate of stretching has been made for the whole sheet swarm (fig. 5B). Two main directions of stretching are thus reconstructed; one is subhorizontal and trends N110°E, the other is subvertical. The subhorizontal extension is clearly related to the set of subvertical sheets, whereas the subvertical extension corresponds to the set of shallowly dipping sheets. If one rotates this plot several degrees to the WNW around a NNE-trending horizontal axis, one obtains two axes of stretching; one is vertical and the other is horizontal and trends WNW. This suggests that subsequent to its emplacement, the sheet swarm was slightly tilted to the ESE.

Two main conclusions follow from this analysis. The first is that the direction of the regional least principal stress axis (σ_3) was WNW during the formation of this sheet swarm. This direction coincides with the current direction of this axis, as inferred for the trend of the neovolcanic rift zone (fig. 1). The second conclusion is that the local stress field associated with the shallow magma chamber of the Kjalarnes central volcano largely controlled the strike and dip of these sheets. This conclusion agrees with results obtained from other sheet swarms in Iceland [Gudmundsson, 1990a].

D) Tectonic lineaments and joints

Most large-scale tectonic lineaments in southwest Iceland strike either NE or WNW (fig. 1). The NE trend can be mostly associated with dykes, normal faults or, in a few cases, joints [Forslund and Gudmundsson, 1991], and these structures are clearly related to the dominating regional stress field associated with the nearby rift zone. The WNW lineaments, however, are not easily explained in terms of the dominating regional stress field.

Many fjords and valleys in southwest Iceland, as well as in many other areas of Iceland, strike approximately per-

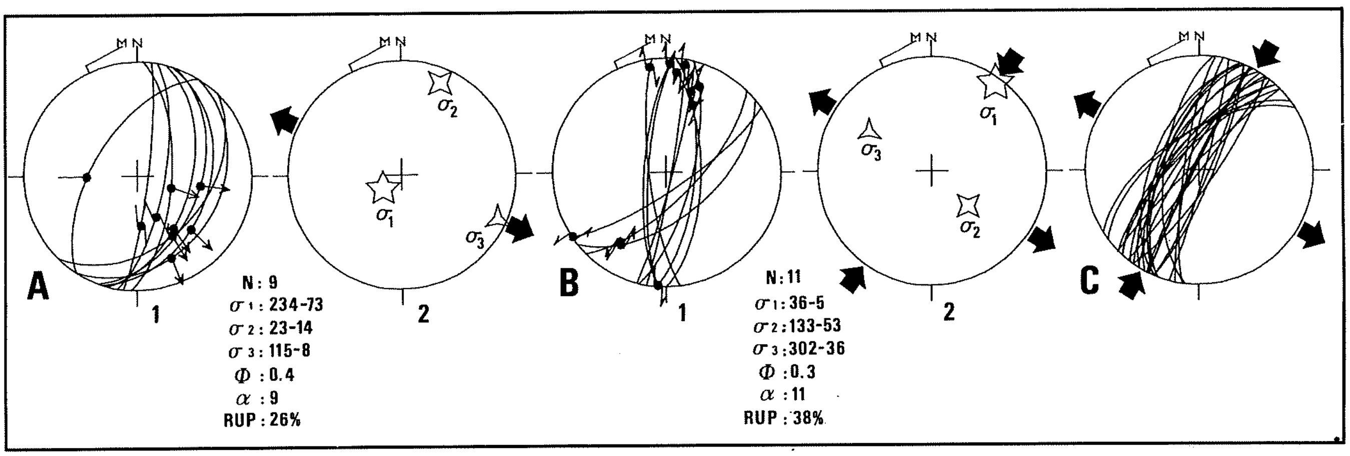

FIG. 6. – Examples of the main stress fields identified in southwest Iceland (lower hemisphere equal area projection).
A and B. – 1 : cyclographic projection of fault planes as thin lines and striations as centrifugal arrows (normal motion) or double arrows (strike-slip motion); 2 : axes of the stress tensor. Large black arrows indicate computed directions of compression or extension. The parameters of the stress tensor determinations are also indicated (all angles in degrees). The attitude of the σ_1 axis in diagram B2 is tightly constrained, whereas the plunges of σ_2 and σ_3 are of less importance (due to the effects of the local stress field associated with the shallow magma chamber of the Kjalarnes central volcano, southwest part of the Esja region). N, number of fault-slip measurements used; σ_1, σ_2 and σ_3, strike and plunge of the principal stress axes; Φ, computed ratio $(\sigma_2-\sigma_3)/(\sigma_1-\sigma_3)$; α, average actual slip-computed shear angle; RUP, deviation estimator ("ratio upsilon"), defined as the modulus of the vectorial difference between slip (dimensioned according to the reduced tensor type) and shear stress divided by the maximum shear stress. It is given as a ratio that ranges from 0-200 %, where values less than 50 % indicate a good fit [cf. Angelier, 1990]; C. – Cyclographic projection of mineral veins.

FIG. 6. – *Exemples de diagrammes caractéristiques des principaux états de contrainte reconnus dans le sud-ouest de l'Islande (projection de Schmidt, hémisphère inférieur).*
A *et* B. – 1 : *projection cyclographique des plans de faille et de leurs stries (flèche centrifuge : mouvement normal, double flèche, mouvement décrochant)*; 2 : *axes du tenseur des contraintes, les flèches noires indiquent les directions de compression et/ou d'extension. Les paramètres calculés du tenseur des contraintes sont indiqués (angles en degrés). Sur le diagramme B2, l'axe* σ1 *est bien définie alors que les inclinaisons des axes* σ2 *et* σ3 *sont moins significatives (liées à des jeux de failles obliques près du centre volcanique de l'Esja).* N = *nombre de mesures utilisées;* σ1, σ2 *et* σ3 : *direction et plongement des axes principaux;* $\phi = (\sigma 2-\sigma 3)/(\sigma 1-\sigma 3)$; α = *angle moyen strie réelle-strie calculée;* RUP : *estimateur d'écart (« rapport upsilon ») défini comme le module de la différence vectorielle entre le glissement (dimensionné suivant le type de tenseur réduit) et la contrainte tangentielle, divisé par le cisaillement maximum et fourni sous forme de rapport de 0 à 200 %, les valeurs inférieures à 50 % indiquant un bon accord [détails : Angelier, 1990]*; C. – *projection cyclographique des veines minérales.*

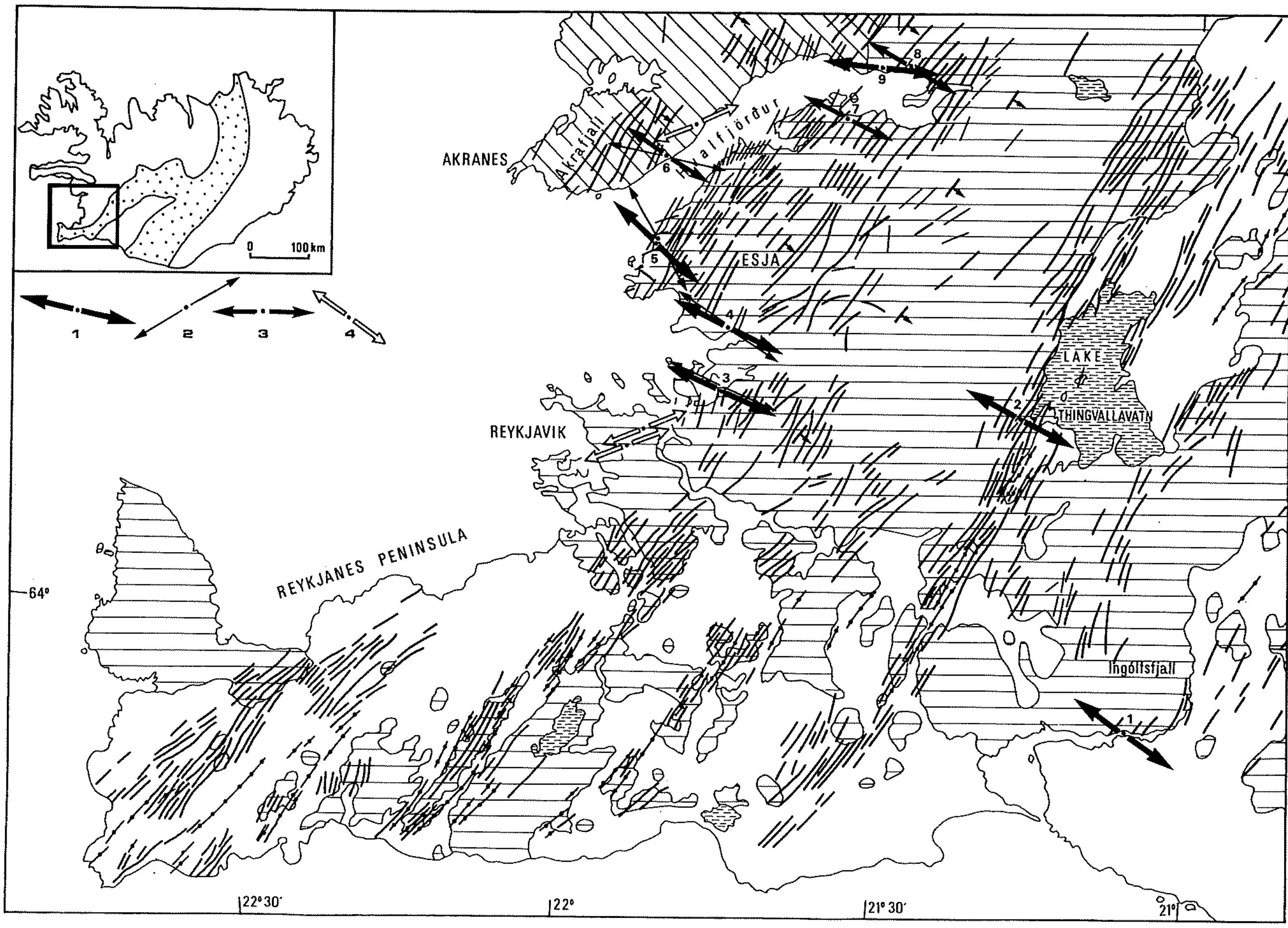

FIG. 7. – Pliocene-Holocene extension in southwest Iceland. See figure 1 for the legend of the map. The indicated trends of extension are from the analysis of (1) normal faults, (2) strike-slip faults, (3) mineral veins. Also shown (4) is the direction of $\sigma_{h(min)}$ from hydrofracturing measurements in drillholes ($\sigma_{h(max)}$ is perpendicular to this direction). See table for more detailed results on paleostress determination from fault-slip data.

FIG. 7. – Extension pliocène à holocène dans le sud-ouest de l'Islande. Voir légende de la carte figure 1. Directions d'extension d'après l'analyse (1) des failles normales, (2) des décrochements, (3) des veines minérales et (4) des mesures in situ ($\sigma_{H(min)}$). *Voir le tableau pour le détail des résultats des calculs de paléo-tenseurs de contrainte.*

pendicular to the main trend of dykes and normal faults. These fjords and valleys have apparently not developed along major faults or dykes as the heads of these valleys are not cut by dykes or normal faults. In many cases, however, the heads of the valleys are dissected by joints [Forslund and Gudmundsson, 1991], suggesting that many fjords and valleys in Iceland develop along joint systems.

There is a noticeable change in the trend of the fjord Hvalfjordur eastwards along its length. The western part strikes NE whereas the eastern part strikes WNW (fig. 1). In order to test if these trends could be associated with joint systems, some 170 major joints were measured at several localities on the north shore and at the head of Hvalfjordur. At all stations there was a strong NE trend of joints. But in the easternmost stations there was a strong NNW-NW trend in addition to the NE trend. This suggests that the change in the trend of Hvalfjordur may be partly related to joint systems that in the inner part of the fjord strike differently from those in the outer part. This observation supports the previous conclusion on the relationship between fracture sets and morphological trends.

IV. – STRESS FIELDS

A) Fault-slip data analysis

The determination of paleostress tensors using fault-slip data is a technique that has been developed in France during the past fifteen years. This technique is usually based on minimising the shear-stria angle [Carey and Brunier, 1974; Angelier, 1979, 1984; Etchecopar *et al.*, 1981]. Recently, a new method for determining the reduced stress tensor was presented by one of us [Angelier, 1990]; it was applied to the fault-slip data sets collected in Iceland during the past three years [Bergerat *et al.*, 1988, 1990]. This new method not only minimises the angles between the theoretical shear stress and the actual slip vector but also ensures that shear stress magnitudes are as large as possible (large enough to induce slip). Because we use this dual criterion, the angular fit, when considered alone, may be not quite as good as that obtained from the purely angular criterion, but the level of shear stress acting on each fault, as obtained from the dual criterion, is more realistic. When the stress tensor is tightly constrained by the fault slip data sets, however, the results obtained from the dual criterion are similar to those obtained from the angular criterion [cf. Angelier, 1990]. Figure 6 (A, B) illustrates such inversion of typical fault-slip data sets from southwest Iceland.

We collected most of the slip-data from southwest Iceland in the Hvalfjordur area and in the Pleistocene area south of lake Thingvallavatn (fig. 1). The results are shown in figure 7. The features that easily reveal the sense of movement on fault surfaces, such as mineralised steps along striae, are present in volcanic rocks, but are less frequent than in sedimentary rocks. In most volcanic rocks, which dominate in Iceland, the identification of shear senses, which plays a major role in paleostress analysis, is difficult. Fortunately, however, other criteria could be used, including observation of Riedel-type fractures or of asymmetric facets, i.e., polished knobs facing the movement of the opposite block and rough facets on the opposite side of the fault surface [cf. Petit, 1987].

Although striated fault surfaces are rather rare in the volcanic formations of Iceland, we could nevertheless make about 600 measurements at several sites in southwest Iceland. Most of these sites provided heterogeneous data sets, but such sets are commonly related to two or more paleostress states corresponding to extensional regimes as well as strike-slip regimes. Criteria to determine the relative chronology are scarce, so that in most cases the fault-slip data subsets were eventually distinguished on the basis of mechanical consistency.

The analysis of subsets of normal faults indicates paleostress tensors with subhorizontal σ_3 axes trending N110-130°E (fig. 6A) or, locally and rarely, N140-150°E [Bergerat *et al.*, 1990]. This slight difference in the reconstructed paleostress tensors may be related to two distinct extensional events or to some fluctuations in the stress field associated with extensional tectonics. The dominant WNW extension is though clearly perpendicular to the rift axis, which in this area trends NNE (fig. 7).

Strike-slip fault systems occur at some sites. Most of them are related to σ_1 and σ_3 axes which are subhorizontal and trend approximately N35°E and N125°E, respectively (fig. 6B).

The average direction of extension, i.e., the computed σ_3 axis, is WNW and is the same for normal and strike-slip faulting. This suggests that the separation between dominant strike-slip and dominant normal dip-slip faulting, made within our data sets on the basis of geometrical analysis, does not reflect significantly contrasting tectonic events. It rather reflects stress permutations σ_1/σ_2 related to variations in the ratio Φ between the principal stress differences (table I).

At some sites in Iceland, including the Esja area, the reconstructed directions of the subhorizontal σ_3 axes differ from those above [Bergerat *et al.*, 1990]. These directions, N to NE, are related to different systems of small-scale strike-slip or normal faulting. Several hypotheses have been proposed to explain this tectonic phenomenon, such as the local stress fields associated with shallow magma chambers and dykes [Anderson, 1936; Pollard and Segall, 1987; Gautneb *et al.*, 1989].

TABLE. – Results of paleostress determinations using fault-slip data from southwest Iceland.
Columns : site number as in figure 7; dominant fault regime (NF, normal faulting; SSF, strike-slip faulting); N : number of striated faults; strike and plunge (in degrees) of the computed principal paleostress axes; Φ, ratio of the principal stress differences, $\Phi = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$; α, average actual slip-computed shear angle; RUP : average ratio of the direct inversion method [cf. Angelier, 1990].

TABL. – *Détermination des paléo-tenseurs de contrainte d'après les données de failles et micro-failles striées dans le sud-ouest de l'Islande.*
De gauche à droite : n° du site (voir localisation fig. 7), F : *régime dominant* (NF : *failles normales,* SSF : *failles décrochantes*), N : *nombre de mesures utilisées, direction et plongement (en degrés) des axes principaux,* $\phi = (\sigma2 - \sigma3)/(\sigma1 - \sigma3)$; α = *angle moyen strie réelle-strie calculée ;* RUP = *rapport moyen de la méthode d'inversion directe [Angelier, 1990].*

Site	F	N	σ1	σ2	σ3	Φ	α	RUP
1	NF	6	250-73	29-13	122-11	0.2	16	31
2	NF	15	286-78	24-2	115-12	0.3	14	44
3	NF	9	95-74	195-3	286-15	0.4	17	35
3	SSF	8	20-11	200-79	290-0	0.3	17	42
4	NF	9	234-73	23-14	115-8	0.4	9	26
4	SSF	11	36-5	133-53	302-36	0.3	11	38
5	NF	8	174-72	49-10	316-14	0.3	8	24
6	SSF	11	58-35	245-55	151-3	0.9	12	33
9	NF	12	257-69	6-7	98-20	0.4	10	32
10	SSF	21	195-11	336-75	104-9	0.4	17	51

B) Extension fracture analysis

Tension gashes and mineral veins are mostly pure tension fractures (mode I fractures). Individual tension gashes may, however, be oblique to the σ_3 axis of the regional stress field. Consequently, determination of the orientation of σ_3 based on the analysis of tension gashes needs a careful statistical analysis. Where tension gashes form a regular set of parallel fractures, the individual fractures of the set normally develop in a direction that is perpendicular to the local direction of σ_3.

The mineral veins at most sites studied in southwest Iceland form regular sets (fig. 6C). On a regional scale, these sets show an overall NNE trend, similar to that of the dykes (fig. 1). Although there is some azimuthal dispersion of these sets, probably reflecting the presence of the shallow chamber associated with the Kjalarnes central volcano, most sites show a consistent average trend of extension (fig. 6C). These results are in good agreement with those obtained from the fault-slip data and confirm that the direction of the main extension in the area was WNW (fig. 7).

C) Hydrofracture and earthquake data

Hydrofracturing stress measurements have been carried out at several sites in southwest Iceland, both in the Pleistocene area of Reykjavik as well as in the Tertiary area of Akrafjall [Haimson and Rummel, 1982]. The test holes are 100-400 m deep. The main result is that the maximum horizontal compressive stress axis ($\sigma_{h(max)}$) is everywhere approximately perpendicular to the currently active volcanic rift zone. The associated vertical stress was calculated from the overburden pressure. In one hole out of three the maximum horizontal stress was higher than the calculated vertical stress at depths shallower than 250 m, but lower at greater depths. Similar depth-dependent changes in the stress field occur in the Reydarfjordur drill hole in the Tertiary area of East Iceland.

The Reykjanes Peninsula (fig. 1) is one of the most active seismic zones in Iceland. An 8-day swarm of earthquakes, occurring in a 12 km-long and 1-2 km-wide seismic zone on this peninsula in 1972 was analysed by Klein *et al.* [1977]. The 2500 recorded earthquakes had hypocentral depths mostly between 2 and 5 km. The 433 focal mechanism solutions indicate that the axis of the minimum compressive stress is horizontal and strikes NW, approximately perpendicular to the direction of the fissure swarms in this area. Most of these solutions indicate normal or oblique-normal faulting. In the centre of the seismic zone there is, however, a region where strike-slip faulting dominates at depths of less than 3 km but normal faulting at greater depths.

In the Pliocene-Pleistocene part of the Borgarfjordur region, just north of the area covered in figure 1, an earthquake sequence occurred in 1974 [Einarsson *et al.*, 1977]. Some of these earthquakes could be associated with normal faults of different strikes, but the main earthquake occurred on an NE-trending normal fault. Surface displacement in soil attained several tens of centimetres and the sense of motion was dip-slip, in accordance with all focal mechanisms solutions obtained during this earthquake sequence.

D) Regional stresses

All the above results indicate that the dominating stress field in southwest Iceland is such that the minimum compressive stress axis (σ_3) trends approximately NW, the intermediate axis (σ_2) trends approximately NE, and the maximum compressive stress axis (σ_1) is vertical. This conclusion is supported by the NE trend of the regional dykes (fig. 1), most of which are pure extension fractures formed in a direction perpendicular to σ_3, by the dominating NE trend of the normal faults, and by the data on joints, mineral veins, slickensides and earthquakes.

The slickenside data, as well as part of the earthquake data, indicate, however, that there is also a strike-slip component on many minor faults. In addition, a few major faults show evidence of strike-slip movement. The present stress field in the Pliocene-Pleistocene areas would also favour some strike-slip movement as $\sigma_{h(max)}$ is not quite perpendicular, but rather oblique, to the dominant NE trend of the normal faults.

V. – Geodynamic implications

From the data presented above we infer that the process of crustal spreading in southwest Iceland occurs in several steps. The main steps, according to our interpretation, are as follows.

Most faults and dykes form within the active rift zone where the time-averaged regional stress field is such that σ_3 is horizontal and trends NW, σ_2 is horizontal and trends NE, and σ_1 is vertical. Some joints, which may be the deepest parts of tension fractures originating at the surface, especially those that strike NE, are probably also formed in this regional stress field.

The magmatic overpressure associated with dykes can temporarily alter the stress field in their vicinities in such a way that σ_1 becomes lateral and striking NW and σ_3 becomes vertical. This stress field favours sill formation and reverse faulting. Some sills may develop into large crustal magma chambers [Gudmundsson, 1990b]. The high lateral stresses associated with the dykes can also give rise to strike-slip movements on already formed normal faults, especially those that strike oblique to the corresponding dykes. Part of the oblique-slip and strike-slip movements during earthquake swarms may be due to the stress effects of either contemporaneously emplaced, or somewhat earlier emplaced, dykes.

Some joints and faults may be generated, or reactivated, outside the main rift zone, or at its margins, in a stress field where σ_3 trends NE or NNE. We believe that this stress field can be partly attributed to the lateral loading of the crust within the rift zone, giving the horizontal tension in the NE-SW direction at the margins of and outside the rift zone. The whole rift zone in southwest Iceland can then be regarded as analogous to a very large, single mode I fracture loaded by internal pressure. The NW-trending joints and faults are most likely to be generated in this stress field. Furthermore, the trend of some of the large-scale lineaments, such as fjords and valleys, is, as mentioned above, likely to be controlled by weaknesses generated in response to this stress field.

The hydrofracture data, suggesting that $\sigma_{h(max)}$ in the Pleistocene and Tertiary areas is roughly perpendicular to the axis of the Holocene rift zone, can be explained in terms of the crustal spreading model outlined above. As long as spreading continues the high lateral compressive stresses generated in the vicinities of dykes become relaxed so that the stress field changes back to its normal rift zone conditions with σ_3 lateral and trending perpendicular to the axis of the rift zone (i.e., NW). However, once a crustal segment is outside the active rift zone, essentially no stress relaxation takes place and the high lateral stresses (due to dykes) perpendicular to the axis of the rift zone become permanent. Continuous dyke emplacement in the rift zone increases the horizontal compressive stress outside it and may also contribute to $\sigma_{h(max)}$ being approximately perpendicular to the rift zone axis in the older areas adjacent to the Holocene rift zone.

In conclusion, the structural data obtained from the divergent plate boundary in southwest Iceland suggest that although the direction of extension is mostly perpendicular to the trend of the rift zone, there are both local and regional variations in the stress field. These variations are related to (1) stress permutations σ_1/σ_2 which result in changes from normal faulting to strike-slip faulting, (2) change in the direction of σ_3 from being approximately perpendicular to being nearly parallel to the trend of the rift zone at its margin, and (3) local stress fields associated with crustal magma chambers, which control the emplacement of the associated dykes and inclined sheets. In addition, short-term local stress fields associated with dyke emplacement may be lead to strike-slip or reverse movements on already formed normal faults.

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