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THE DYNAMICS OF FAULTING
AND DYKE FORMATION WITH APPLICATIONS TO BRITAIN

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PREFACE

The dynamical conclusions of this volume are mainly those of the author. The applications are, on the other hand, based almost entirely on the work of others, including that of the Geological Survey. Thanks are due to so many former colleagues that they can hardly be named individually. Reference should, however, be made to the help received from the study of the dykes of Scotland by Dr J. E. Richey. Some of the line-blocks which illustrated Dr Richey's paper on the subject have been made use of in this work, by the courtesy of Edinburgh Geological Society. I am also indebted to Dr M. MacGregor and Dr W. Q. Kennedy, of the Survey, and to Professor W. T. Gordon, all of whom have kindly read the manuscript, and made suggestions.

The conclusions arrived at have not always been endorsed by my colleagues, and must in some cases be left to the test of future investigation. The research is one of considerable interest, as well as importance, and it is hoped that it will appeal to others. Publication has been facilitated by a grant from the Scottish Universities Carnegie Trust, for which I wish to record my thanks.

E. M. ANDERSON

1942

PREFACE TO SECOND EDITION

OWING in part to the cessation of purely geological research which was caused by the war, it has not been necessary to make many additions to the second edition of this memoir. The plates which were kindly lent by Dr Richey and Edinburgh Geological Society have again been put at the disposal of the publishers, and have contributed very much to the effectiveness of the work.

E. M. A.

1951

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CHAPTER I

INTRODUCTION

THE study of the fractures which dissect the earth's crust is a branch of tectonics, the wider subject which deals also, and perhaps mainly, with folds and distortions. These are so closely related to faulting that it might be thought impossible to treat the two branches separately. But the theory of fault and dyke formation is comparatively simple. It may afford a clue to other, more general tectonic problems, and can well, on this account, be considered independently.

The occurrence of faults and dykes must have been known from the earliest days of mining. It was only gradually, however, that they became an object of scientific study. Vallisnieri, writing in 1721, described the faults and dislocations of the strata in the Alps and other chains, and is quoted by Lyell (8, p. 43). Hutton, in '*The Theory of the Earth*', says 'without any change in the general direction of the stratum, miners often find their coal broke off abruptly, those two parts being placed upon a higher and a lower situation in respect to each other, if flat beds, or separated laterally, if edge seams. This is by miners termed a slip, hitch, or dyke' (6, p. 595). In another part of this classical composition an instance is given of a 'slip or hitch' near Newcastle, running for 17 or 18 miles, on one side of which corresponding strata were found at a level 70 fathoms lower than on the other (7, pp. 289-290). The existence of faulting was therefore well known in this country in 1795, and, without doubt, it had been discovered much earlier.

Playfair, writing in 1802, refers to flips and, to 'a fault, throw, or break, or what we have here called a shift', found in digging a canal in Yorkshire. The evidence, although suggestive, does not seem so conclusive that the structure in question was a fault as in the instances given by Hutton, but the citation may, nevertheless, be of interest, as an early example of the use of the term 'fault' in geological literature. Playfair also mentions that certain mineral veins may cross and 'heave' the other veins of a district (12).

Lyell's reference to Vallisnieri has already been mentioned, but the former, in the *Principles of Geology*, says comparatively little about faulting. During the last century, with the progress of geological mapping, these dislocations came gradually into prominence, and before the end of that period the three principal classes into which faults can be divided had been clearly recognized. This was partly, no doubt, owing to the able analysis which was made by Suess, who collated the results of previous workers, and divided fault movements into tangential and radial (14). The former class he subdivided into 'Wechsel' or overthrusts, and 'Blätter'. The term 'Blatt' will be translated as wrench fault; the different English equivalents will be discussed in Chapter V. Normal faults were designated as radial.

It is necessary, at this stage, to indicate very briefly the distinctions of the three classes, although they are familiar to all geologists. Overthrusts, or more simply thrusts, are faults which are inclined, in theory, at well under 45° to the horizon, and in field experience it is found that they are sometimes nearly horizontal. The rock which forms the overlying or 'hanging' side of the thrust has been impelled directly, or almost directly, *up* the slope of the fault-plane. This, at least, has been its relative movement. (It is seldom, or never, possible to judge about absolute movement, and this proviso will be understood in what follows.) As the slope is a low one, the movement is more nearly horizontal than vertical, and a thrust fault may therefore be classed as tangential.

A Wrench Fault is a nearly vertical fracture, along which the separated segments have slid in a horizontal or nearly horizontal manner. Here again there is 'tangential' movement. Normal Faults are, in theory, steep, but not vertical. Their angle is usually found to be well over 45°. The overlying block has, in this case, moved directly, or almost directly, *down* the slope of the fault-plane. The movement is thus, owing to the inclination, more nearly vertical than horizontal, and a normal fault may thus be classed as radial.

These definitions are not intended to be critical, or to include every case of faulting. It may be said, however, that the majority of faults can easily be assigned to one or other of the three classes. In other cases data may be wanting to make the assortment, and a few dislocations may not, in theory, belong to any of the three.

The above subdivision refers, however, only to faulting, and this is not the only type of fracture with which geologists have to deal. Rupture, in some form or other, has probably occurred along with most cases of igneous intrusion. In a few instances it is quite easy to show that this fracture has taken the form of faulting. With regard to sills, however, and the majority of dykes, it is evident that some other mechanism has been involved. Dykes, in particular, are not usually accompanied by much relative movement of the two sides in a direction parallel to their planes.

To return to the history of investigation, it has been left, in the main, to the engineering profession to experiment with fracture, and to formulate its theory. It is only to a very limited extent, it must be confessed, that the theory is yet known. At an early date, however, it must have become evident that there are two distinct types of fracture. There is, in the first place, tensile fracture, along planes which are normal to the direction of maximum tension in the tested specimen. This can only take place, presumably, when there is at least one direction of tension, but the other type, known as shear fracture, may occur both when there is and when there is not tension, if the stresses in different directions differ sufficiently from one another. Shear fracture develops along planes which correspond, in theory at least, more nearly to those across which there is a maximum tangential stress, than to those across which there is a maximum tension, if tension be present. The two classes of rupture are therefore fundamentally different.

When this became known, it was easy to explain the distinction between faults and dyke fissures. The former are shear fractures, and their method of formation is treated, on this basis, in Chapter II. Dykes, on the other hand, are intruded along tensile fractures, the dynamics of the process forming the subject of Chapter III. It would be difficult to say, however, when engineering investigators first made the discovery, or who first suggested its application to geology.

The theory of shear fracture, referred to above, is assigned to Coulomb, and this is, in all probability, correct, although the writer is unable to quote the text of any publication in which the principles are stated very definitely. An important advance was made by Navier in 1833 (11). The planes of greatest shearing stress bisect the angles made by the directions of greatest and least pressure, but experiment shows that rupture does not occur exactly along these planes. Navier explained this by assuming a 'coefficient of internal friction', which he regarded as constant. His process of reasoning is essentially the same as that which has been adopted in Chapter II.

Mohr's much later work may be described as a generalization of Navier's principle (9). He did not regard the 'coefficient' as constant, but variable with regard to the transverse pressure. Navier's and Mohr's hypotheses both lead to certain limiting relations between the principal stresses, which must hold at the moment of fracture, but these are not the only relations which have been suggested. There is also, for instance, Von Mises' criterion, which states that if P, Q and R are the principal pressures, or tensions, as defined in Chapter II, the limiting condition is that $(P-Q)^2+(Q-R)^2+(R-P)^2$ shall be equal to a certain constant, depending on the material.

The first application of the general theory of shear fracture to geology was perhaps that which was made by Hopkins in 1849 (5). He did not, however, use Navier's modification, and his object was to explain rock cleavage rather than fracture.

Of the three directions of principal pressure, in country which is not Alpine in its topography, and at moderate depths, one must in general be nearly vertical, and two nearly horizontal. In a paper published by the writer in 1905, this principle was assumed without proof (1). An *a priori* proof is, in fact, somewhat difficult, although it is attempted in Chapter VII. It was, nevertheless, by an application of the principle that the writer succeeded, he believes for the first time, in explaining the three main classes of faulting. It was also shown in this paper that Navier's modification is necessary, to explain the inclination of thrusts and normal faults.

Navier's principle is not only necessary, but sufficient to explain all that is yet certain about the limiting stress conditions, and the directions of rock fracture, in the upper part of the crust. The experiments of Kârmân, and of Adams and Bancroft, show that, at yielding point, there are relations between maximum and minimum pressure which may be 'linear' within the limits of error (see Chapter VII). This may hold up to large transverse pressures for granite and basalt, and for sandstone and marble as far as these are susceptible to actual fracture. It is therefore unnecessary to assume that there is any variation in the 'coefficient of internal friction', such as is supposed by Mohr.

Von Mises' principle does not, in itself, explain these experiments. It is possible that the two conceptions are not antagonistic, but mutually complementary. So far, however, there is no definite proof that any but the Navier principle need be applied, in dealing with the upper crust.

Daubrée's experiments have so often been quoted, in connexion with faulting, that it is necessary to refer to them, even in this brief historical account (3). The best known tests consisted in the fracture of rectangular pieces of glass by torsion applied to their ends. By this means double systems of breakage were obtained, forming angles of about 45° with the edges of the rectangles, and approximately at right angles to one another. These results have been largely cited as explaining the origin of 'conjugate' systems of faults. Certain considerations suggest, however, that the breakages were instances of tensile and not of shear fracture (*see* p. 22). They can thus have had no relation to faulting.

Daubrée's experiments on the effect of unilateral pressure on prismatic test-pieces are, on the other hand, more relevant. He obtained double systems of fracture, diverging a little from the planes of maximum shearing stress, in the directions required by Navier. The material tested was 'mastic', but similar trials have repeatedly been carried out on actual rock materials. In most cases the results have been similar. Gulliver, for instance, gives the angle between the applied pressure and the surfaces of sliding as being from 25° to 28° for sandstone, and from 20° to 25° for limestone (4). Experimental yielding of different types has been specially studied by Nadai, who figures, among other things, the development of shear fracture in sandstone and marble (10).

Attention may be drawn here to the report of a committee on the nomenclature of faulting, which was published in 1913 in a Bulletin of the Geological Society of America (13). A useful series of references, bearing on the historical side of the theory, has been given by the late Professor H. Briggs (2).

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CHAPTER II

THE DYNAMICS OF FAULTING

IN dealing with the dynamics of faulting the terms pressure, tension, and shearing or tangential stress will be in constant use. The first two hardly require definition, yet it is necessary to call attention to occasional misconceptions about their meaning. Pressures and tensions are not, in the dynamical sense of the word, forces. It is true, however, that they imply the mutual exertion of forces between different parts of the media in which they occur. A force only acts on an element of solid in one direction, say from north to south, and if, in this case, another force impels the element from south to north, the two are not identical, but contrary. A pressure or a tension, on the other hand, implies that two such contrary but balancing forces act on the same element at once. It is thus strictly incorrect to speak of a pressure as coming from any one direction, such as the north, and this, although it is elementary, is sometimes forgotten by writers on geology. Attempts are then made to combine or resolve pressures according to a triangle of forces. It is true that pressures may be combined, but the results are quite different from any which can be obtained by such a method.

In the third type of stress, which is denoted tangential or shearing stress, one is also dealing with contrary and balancing forces, but there is a difference in the way in which these are applied. Suppose two parts of a solid block to be separated by an imaginary plane, which is vertical and extends from west to east. There may then be either pressure or tension across this plane, but independently of this the northern half of the block may exert a lateral force upon the southern, impelling it, say, towards the east. The southern half must then exert a westerly force upon the northern, and this mutual interaction is an example of a shearing or tangential stress, in which the imaginary plane is a plane of shear.

It should be noted that the word 'stress' by itself may mean either a shearing stress, or a pressure, or a tension. It can be shown mathematically that, in a solid under strain, there will in general be shearing stress across a plane which is selected at random. In the neighbourhood of any particular point, however, there are three intersecting planes, across which there is no tangential stress, but only, in each case, a pressure or a tension. The three planes are at right angles to one another, so that their normals are also the directions of intersection. The pressures or tensions referred to are called the 'principal stresses', the planes the 'principal planes', and the normals the 'principal directions' of stress.

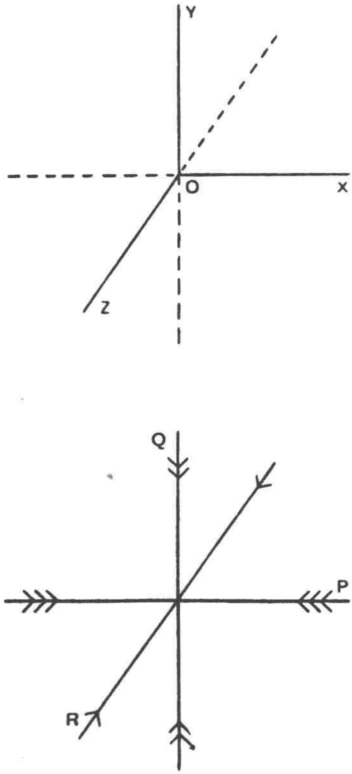

FIG. 1.—Principal directions of pressure (or tension) forming a rectangular system.

The above statements form part of the well-known dynamical theory, given in every text-book which deals with stresses in solid bodies (see, for instance, (3), p. 81). The only modifications needed arise when two or more principal stresses are equal. Cases where this occurs will be referred to later. In the meantime it will be assumed that these stresses are all unequal. According to theory there will then be two plane directions across which tangential stress is a maximum, and this must obviously have a bearing on the directions of shear fracture.

Suppose O to be the point in the solid referred to (Fig. 1), and let OX, OY, and OZ be the directions of the principal stresses. Let the pressures or tensions acting along these lines be P, Q and R, which we will suppose positive when they denote pressures, and negative when they refer to tensions. Suppose further that P is the greatest pressure, or the least tension in the case when there are only tensions, and that R is the greatest tension, or the least pressure when there are only pressures, so that P, Q and R are algebraically in descending order of magnitude. Theory then shows that the planes