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Cone-sheets and Ring-dykes: the dynamical explanation

(With 1 text-figure)

The term « central intrusions » might be applied to any system of dykes, sills, or inclined sheets which were known to be intruded from some definite centre. The present communication deals with two classes of such intrusions, which form arcuate outcrops, arranged in series, round more or less identical centres of curvature.

The two classes referred to are those which have been named cone-sheets and ring-dykes by E. B. Bailey (2). Cone-sheets were first definitely recognized in Skye by Harker. They were first described in Mull by W. B. Wright, who published a section showing their extreme abundance (6), and was followed by other members of the Scottish Geological Survey. Ring-dykes were first mapped by Nolan and others, in the Slieve Gullion district in Ireland, and they have been found to occur in Mull in large numbers. Both types of intrusion are well developed in Ardnamurchan. Similar structures also occur round three centres in Northern Ireland, where, as in the Ardnamurchan example, they have been described by J. E. Richey (4, 5).

The Scottish and Irish examples are in the meantime to be regarded as the types, but ring-dykes occur in South Africa, (Pilansberg), and round more than one centre in North America. What appears to be a system of very thick cone-sheets has been described by A. D. N. Bain in Nigeria (3), and it seems probable that, as investigation proceeds, the known cases of both types of intrusion will be increased.

Cone-sheets are typically comparatively narrow (3 to 15 metres) and very numerous. They incline towards their centres at angles which vary from about 35° to 60°. Ring-dykes are fewer and wider (say 50 to 2000 metres), and are either vertical, or dip away from their centres at steep angles. The two classes are in several instances found to surround the same centre. Where they do so their relations are shown diagrammatically by Fig. 6 of Dr. RICHEY's paper (p. 23).

In the Mull Memoir (2) an attempt was made by the present author to explain the two different types of intrusion by stresses set up in the rocks by fluid magma occupying a subterranean caldron. This cavity must be supposed to have a somewhat dome-shaped upper surface, while it may extend downwards to a considerable depth. Its apex is directly beneath the centre of the cone-sheet or ring-dyke system, at a distance from the original surface of only a few kilometres. The formation of cone-sheets may then be explained by supposing the magma to be under a pressure which is greater than that caused by « head » in the surrounding rocks. It will thus have a tendency to « lift its roof ». This may be dynamically expressed by saying that there is extra pressure, in a vertical direction, immediately above the dome. In the horizontal direction, however, there is a relief of pressure. This is analogous to the fact that there is tension, in the direction of curvature, along the walls of a boiler. In the present case the magma pressure is insufficient to give rise to tension, but the relief of pressure will follow surfaces which run parallel to the walls of the cavity, and will thus have an outward inclination, increasing with their distance from the apex (Fig. 1).

Under these circumstances intrusions of magma may form, and may penetrate into, fissures which are analogous to tension fractures. Their directions will be perpendicular to the « principal stress » in the rock which comes nearest to being an actual tension. They will thus be normal to the walls of the basin. There is however more than one set of surfaces which has this normal character. One set will radiate from the centre, and in this way one may explain the radial dykes which perhaps exist in Skye, and certainly occur in one case in America. In the particular instance which is illustrated in Fig. 1. the closest approximation to a tension is usually in the plane of the diagram. In such a case the intrusions will not be radial, but will surround the centre in the form of cone-sheets. The inner

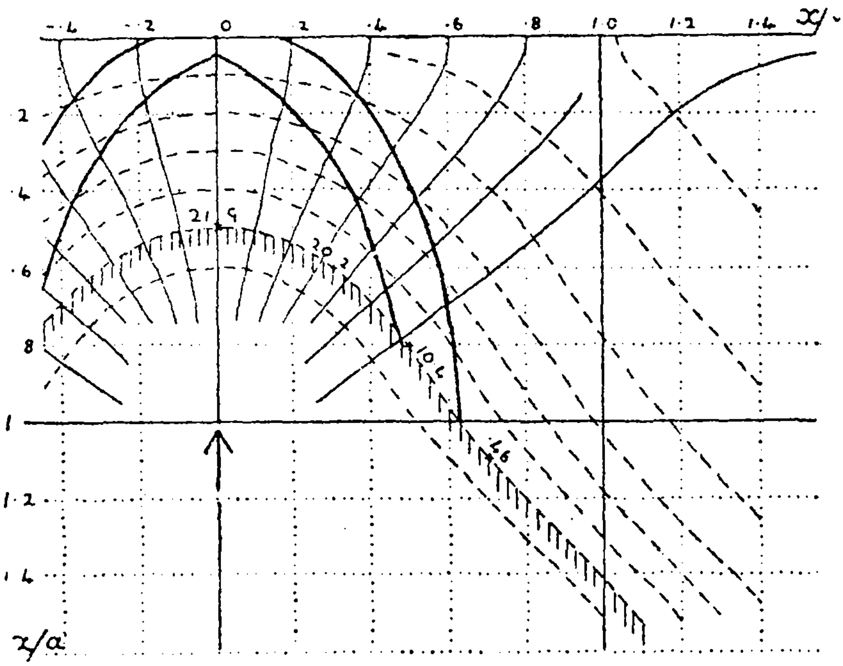

Fig. 1. — Formation of Cone-sheets and Ring-dykes. For explanation see text. Reproduced, with permission, from Proc. Roy. Soc. Edin., vol. 56, p. 144.

sheets of a system are sometimes the steeper, as shown by the text-figure.

Ring-dykes, of the other kand, were explained by supposing that, when they were formed, the pressure in the magma basin had sunk to below that normally due to gravity at an equal depth. In this case the fractures which are occupied are not directly formed by the magma, but only indirectly, owing to stresses produced in the rock. They are shear fractures, as opposed to tension fractures, and the intrusions may, in some cases, be of somewhat later date. To produce any of the larger ring-dykes, however, there must be a rupture which forms a closed curve in horizontal section. This must extend downwards to the magma basin, and the block within it must, for some reason or other, be free to sink. According to te theory put forward, there is an outward inclination of this fracture. During subsidence the block therefore parts company with its surroundings, and the vacancy is simultaneously occupied by magma.

It would be incorrect to regard such an intrusion as due to suction. A fluid under gravity must always to some degree be under pressure. But in ring-dyke formation the pressure is less, just as in cone-sheet intrusion it is greater, than that usually characteristic of its level in the crust.

The suggestions put forward in the Mull Memoir, in 1924 were not at the time supported by any rigid mathematical theory. It was not until ten years later that formulae were found showing how, with certain shapes of basin, and certain distributions of pressure along their walls , the stresses necessary for cone-sheet and ring-dyke formation are bound to arise (1). The principal directions of stress given by one set of formulae are shown in Fig. 1. Here the shaded margin may be taken to be a vertical cross section of the edge of the magma basin. If there is excess of pressure in the caldron, there will be a relative tension which is greatest across the surfaces indicated by the fine firm lines, with consequent production of cone-sheets in these directions. If there is defect of pressure in the basin, there will be relative tension across the surfaces whose intersection with the plane of the diagram is given by the broken lines. There has not, however, been intrusion of magma along these surfaces. The heavy lines are drawn at angles of about 25° to the broken lines, and are intended to represent the course of possible shear fractures. In their lower parts, at least, they correspond in inclination with ring-dykes.

Many difficulties, of course, remain. It is impossible as yet to say why in some circumstances a rock, or any other solid, will yield by shear fracture, and in other cases by tension fracture. Both types do exist in the crust, as the one class is exemplified by faults. and the other by ordinary dykes. It has also been objected that the systems of stress given by the formulae only occur before rupture. When even a single fracture has been formed, a system will be more or less modified. This is true, but the accordance of fact with theory is so good that the first stage of an explanation would seem to have been reached.

The shape of caldron shown in the diagram, with the relative pressures indicated along its margin, form a system which lends itself to calculation. This system is not however regarded as being actually the most probable. Certain difficulties may be avoided if the basin has more nearly the form of an « inverted flower-pot », with a somewhat angular edge. The variations of pressure in the basin may perhaps be explained as follows. One may suppose the caldron to open downwards into a shallow horizontal reservoir, of great lateral extent. Within such a reservoir pressure will be determined almost solely by the weight of the overlying rock. It will therefore be neither in « excess » nor in « defect ». Suppose however that the magma in the caldron is lighter than the rock which surrounds it. Molten basalt at the surface has a density of apout 2.59, so that this may well be the case. There will then be a smaller vertical gradient of pressure in the magma than in the rock. It follows that there will be « excess » of pressure in the magma basin, increasing towards the top. The defect of pressure which leads to ring-dyke formation may be explained most easily by a reduction of the volume of the magma. This may perhaps be caused by cooling, with partial consolidation. In order that this may be effective there must be elimination of the conditions which would lead to excess of pressure, and this may happen if the consolidation interrupts the continuity of the supposed horizontal reservoir.

Thanks are due to the Council of the Royal Society of Edinburgh for permission to reproduce the text-figure.

REFERENCES

1) ANDERSON, E. M. — *The Dynamics of the Formation of Cone-sheets, Ring-dykes, and Caldron-subsidences.* Proc. Roy. Soc. Edin., vol. 56, pt. 2, 1936, p. 128.
2) BAILEY, E. B., CLOUGH, C. T., WRIGHT, W. B., RICHEY J. E. and WILSON, G. V. — *Tertiary and Post-Tertiary Geology of Mull, Loch Aline, and Oban.* Mem. Geol. Surv. Britain, 1924.
3) BAIN, A. D. N. — *The Younger Intrusive Rocks of the Kudaru Hills, Nigeria.* Quart. Journ. Geol. Soc., vol. 90, 1934, p. 201.
4) RICHEY, J. E., and others. — *The Geology of Ardnamurchan, North-west Mull and Coll.* Mem. Geol. Surv. Britain, 1930.
5) ——— — *Tertiary Ring Structures in Britain.* Trans. Geol. Soc. Glasgow, vol. 19, pt. 1, 1932, p. 42.
6) WRIGHT, W. B. — in *Summary of Progress of the Geological Survey for 1910,* Mem. Geol. Surv. Britain, 1911, pp. 31-38.