Magnetic Anomalies over a Young Oceanic Ridge off Vancouver Island
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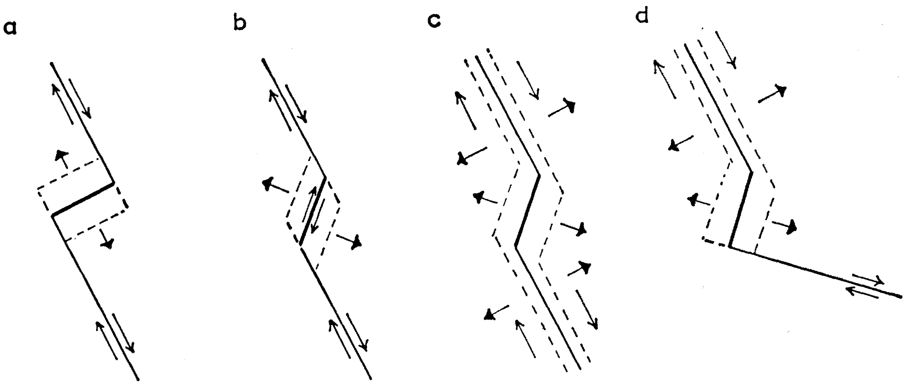

Fig. 4. Diagram illustrating variations in the transform of mid-ocean ridges to transform faults, depending upon the angles of junction and directions of motion.

In Fig. 4*c* the tensional forces are perpendicular to the ridge producing purely tensional rifting across it which requires the faults to open as well as to shear. In this case there could again be a complete lack along the ridge of any earthquakes due to shearing. It is suggested that this is an idealization of the case which we have been discussing. It can account for the lack of seismicity along the ridge, the uniformity of the anomalies, and the existence of areas of irregular anomalies. Obviously a full explanation of the irregular anomalies will require more consideration, but the motion in Fig. 4*c* agrees with that favored by Bailey, Irwin, and Jones for the San Andreas fault (*16*).

Figure 4*d* illustrates a still more complex case in which neither are the transforms between faults and ridges orthogonal, nor are the faults parallel with one another. Transform junctions at acute angles would introduce compression along faults as well as shearing. In practice many more complexities can be expected.

If this interpretation is correct the whole floor of the Pacific Ocean from the East Pacific Ridge has been moved northward towards the Aleutian Trench, bearing the Mendocino and other, older fracture zones with it. Therefore, they are not related to structures on the continents with which they happen at present to be aligned.

R. G. Mason, from a study of magnetic anomalies, and H. H. Hess, from a consideration of measured heat flow, have both independently proposed to me in discussion that there may be another young and growing ridge between the Mendocino fracture zone and the Juan de Fuca Ridge. This neat solution also explains the epicenters along the Mendocino and Gorda escarpments (which are not shown by Tocher or in Fig. 3). It has been added as an alternative in Fig. 3 and named the Gorda Ridge, but does not affect the other arguments.

The manner in which seismic activity in the eastern Pacific is concentrated on those parts of the fracture zones lying between apparently offset lengths of the East Pacific Ridge suggests that the Mendocino and other fracture zones parallel with it may themselves be transform and not transcurrent faults, as has heretofore been supposed. If this is so, the offsets in the patterns of magnetic anomalies are not due to displacement by faulting, but are an inheritance from the original shape of the first rift in the floor of the Pacific with which they are connected. According to Menard (*6*), this is the East Pacific Ridge. According to Hess (*17*), it is the Darwin Rise. In either case a new interpretation is needed.

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18. I thank the departments of geodesy and geophysics and of geology, and Churchill College, University of Cambridge, where this report was written, and those on whose published data it is based. I thank Sue Chappell and Sue Vine for preparing the manuscript. I am grateful to Sir Edward Bullard, J. Dewey, D. H. Matthews, A. G. Smith, and F. J. Vine for very helpful discussions and suggestions, and particularly H. H. Hess and R. G. Mason for a major addition by proposing the existence of the Gorda Ridge. This report is a contribution to the Canadian Upper Mantle Project and the Vela Uniform Project.

21 June 1965

Magnetic Anomalies over a Young Oceanic Ridge off Vancouver Island

Abstract. *The recent speculation that the magnetic anomalies observed over oceanic ridges might be explained in terms of ocean-floor spreading and periodic reversals of the earth's magnetic field may now be reexamined in the light of suggested reversals during the past 4 million years and the newly described Juan de Fuca Ridge.*

Surveys of the earth's total magnetic field have been made along closely spaced lines over large areas in the northeastern Pacific Ocean (*1*). These show a surprisingly regular, linear pattern of anomalies, often hundreds of kilometers long and tens of kilometers wide, and usually aligned approximately north-south. Vine and Matthews (*2*) have suggested that these anomalies, together with the central magnetic anomaly observed over certain oceanic ridges, might be explained in terms of ocean-floor spreading (*3*) and periodic reversals of the earth's magnetic field. The idea proposes that as new oceanic crust is formed over a convective upcurrent in the mantle, at the center of an oceanic ridge, it will be magnetized in the ambient direction of the earth's magnetic field. If the earth's field reverses periodically as ocean-floor spreading occurs, then successive strips of crust paralleling the crest of the ridge will be alternately normally and reversely magnetized, thus producing the linear anomalies of the northeastern Pacific. These anomalies are not obviously parallel to any active oceanic ridge, but it seems possible that they are related in this way either to the East Pacific Rise, as suggested by Menard (*4*), or to the extinct Darwin Rise, as suggested recently by Hess (*5*).

At the time it was put forward, the Vine and Matthews hypothesis was particularly speculative in that no large-scale magnetic survey was thought to be available for an oceanic ridge, and results regarding the periodicity, or even confirmation, of possible reversals of the earth's magnetic field were very preliminary (*6*). Recently the evidence suggesting possible reversals of the earth's field has been examined more critically and a periodicity suggested for the past 4 million years (*7*). Furthermore, it has been suggested in the preceding report that the area of detailed magnetic survey in the northeastern Pacific might include one or more short lengths of a young and active oceanic ridge (*8*). This suggestion was originally based on the concept of transform faults and the distribution of earthquake epicenters along the western coast of North America (*9*). Only subsequently was reference made to the magnetic survey (*1*) to find that it lends convincing additional support to the proposal.

Clearly, if these interpretations are correct we now have information with which to reexamine the original suggestion of Vine and Matthews (*2*). If one assumes that there have been major reversals of the earth's field at 1, 2.5, and 3.4 million years and short-lived reversals at about 1.9 and, possibly, 3 million years, as suggested by Cox, Doell, and Dalrymple (*7*), and if one assumes two commonly suggested rates of spreading, 1 and 2 cm per year per limb of the convecting system, one obtains the models and calculated anomalies shown in Fig. 1, *a* and *b*. The models are directly comparable with those originally suggested by Vine and Matthews, that is, the normal and reversed blocks extend from a depth of 3 to 11 km below sea level and have effective susceptibilities of ± 0.0025, except for the central block, for which the value is assumed to be $+0.005$.

The model for the 1 cm per year rate (Fig. 1*a*) suggests a possible explanation for the central high-amplitude anomaly observed over certain oceanic ridges, notably the Mid-Atlantic Ridge and the northwestern Indian Ocean (Carlsberg) Ridge, as discussed previously (*2*). For this rate of spreading, the anomalies resulting from the normal-reverse contacts on either side of the central block reinforce each other to produce the central anomaly. For the faster rate of spreading, giving rise to a wide central block, the reinforcement is much less, and a rather broad central anomaly is produced which is not so easily distinguished from its neighbors (Fig. 1*b*). This might possibly be the case over the East Pacific Rise and the new, Juan de Fuca Ridge (*8*) (see Fig. 2). One would hardly expect the rate of spreading to be constant throughout the life-span of an oceanic ridge, and therefore it is unlikely to be the same for all ridges at the present time.

The essential feature of the Vine and Matthews hypothesis is that the normal-reverse contacts produce the steep, often isolated, magnetic gradients over ridges. On the basis of this criterion the steepest gradients over the Juan de Fuca Ridge have been assumed to delineate normal-reverse boundaries, and a crude model has been drawn up, again along the lines originally proposed by Vine and Matthews. The models and calculated anomalies are presented in Figs. 1*c* and 2*c*; Fig. 1*c* shows the central part of Fig. 2*c*. Despite the simple nature of this model it agrees well with the observed anomalies (Fig. 2*b*). As-

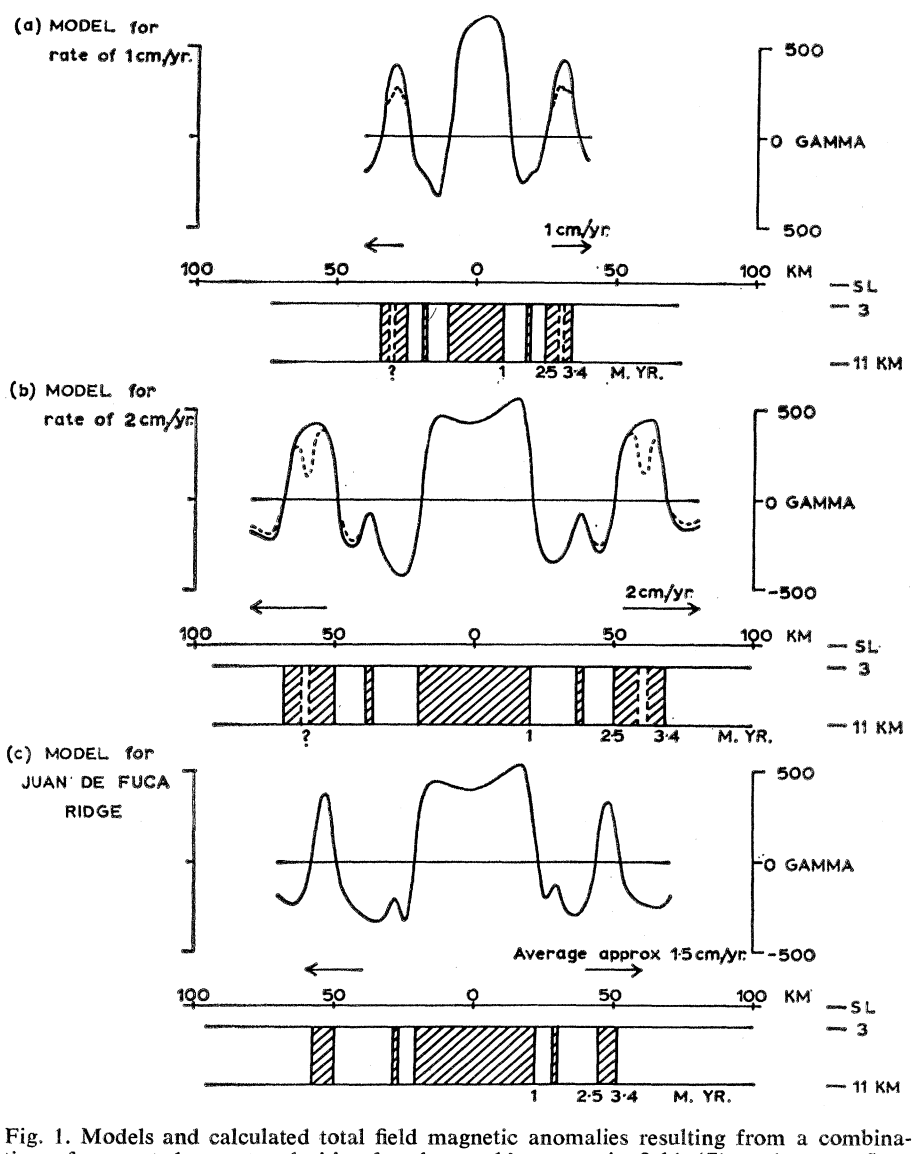

Fig. 1. Models and calculated total field magnetic anomalies resulting from a combination of suggested recent polarities for the earth's magnetic field (*7*) and ocean floor spreading. Normally magnetized blocks are shaded; reversely magnetized blocks unshaded. Portions *a* and *b* assume uniform rates of spreading. Portion *c* was deduced from the gradients on the map of observed anomalies. The dashed parts of the computed profiles show the effect of including the possible reversal at 3 million years (*7*; see also *15*).

suming that the times of the field reversals are the same as those suggested by Cox, Doell, and Dalrymple (*7*), dates have been added to the section and an average rate of spreading deduced (Fig. 1*c*). In Fig. 1, comparison of *c* with *a* and *b* suggests that the rate of spreading of the ridge has been rather irregular, as one might expect, but averages about 3 cm per year (1.5 cm per year per limb of the cell). This implies that the central 120 km or so of the crustal material over the crest of this new ridge has been formed within the past 4 million years. Thus if it is assumed that the rifting and associated faulting has continued without interruption and at this average rate, then the whole ridge (a total width of about 350 km) would be no more than 11 or 12 million years old. These deductions agree well with the rate of movement observed at present along the San Andreas fault (*10*) and with the total displacement across it, as discussed by Wilson (*8*).

Clearly, the models shown in Figs. 1 and 2*c* are oversimplified. However, they express the basic tenet of the Vine and Matthews idea that the steep magnetic gradients so obvious from any detailed magnetic survey over the oceans might delineate the boundaries between essentially normally and essentially reversely magnetized crust, thus reproducing the observed gradients without recourse to improbable structures or lateral changes in petrology. If this basic principle is accepted, there is no difficulty in explaining the anomalies but only in deciding on the distribution of magnetization within the various layers of the oceanic crust (*11*). As ever in the interpretation of magnetic anomalies, there is no unique solution, and the various parameters are so "flexible" that, having assumed normal and reverse strips, the model can be fitted to any existing concept of the structure of oceanic ridges.

Ocean-floor spreading implies that the oceanic crust is a surface expression of the mantle; it must therefore be generated from the mantle and be capable of being resorbed by it, as emphasized by Hess (*5*). Basalt is the most common outcropping hard rock on the ocean floor; if this is regarded as the lowest melting fraction of the material of the upper mantle then it probably represents only a small percentage of this material by volume. Hess considers, therefore, that basalt accounts for only a thin veneer 1 or 2 km thick on top of a main crustal layer of serpentinite, that is, hydrated mantle. The great thickness of basalt lavas in central Iceland (*12*) is clearly anomalous in that the whole crustal section is thicker, and away from the center the volcanics have been subjected to erosion, unlike those of the submarine ridges. Assuming the validity of the model for oceanic ridges proposed by Hess (*5*), the "magnetic" material of the crust would be largely confined to the basalt layer (layer 2). Hess envisages that the serpentinite layer (layer 3) is emplaced in the solid state and it would therefore acquire its remanent magnetization at depth on passing through the Curie point isotherm. By the time it is emplaced beneath the central rift it might well be highly sheared, fractured, and randomly orientated. Serpentinite would appear to be weakly magnetized and to have a Konigsberger ratio of approximately 1 (*13*). All in all it would probably be capable of contributing little to the observed magnetic anomalies. The basalt, however, cools through the Curie point in place in the form of lava flows or intrusives. It is strongly magnetized, and its remanent magnetization probably predominates, since its susceptibility would appear to be comparatively low (*14*). In Fig. 3*c*, the magnetic anomalies have been computed over a model in which the magnetic material is con-

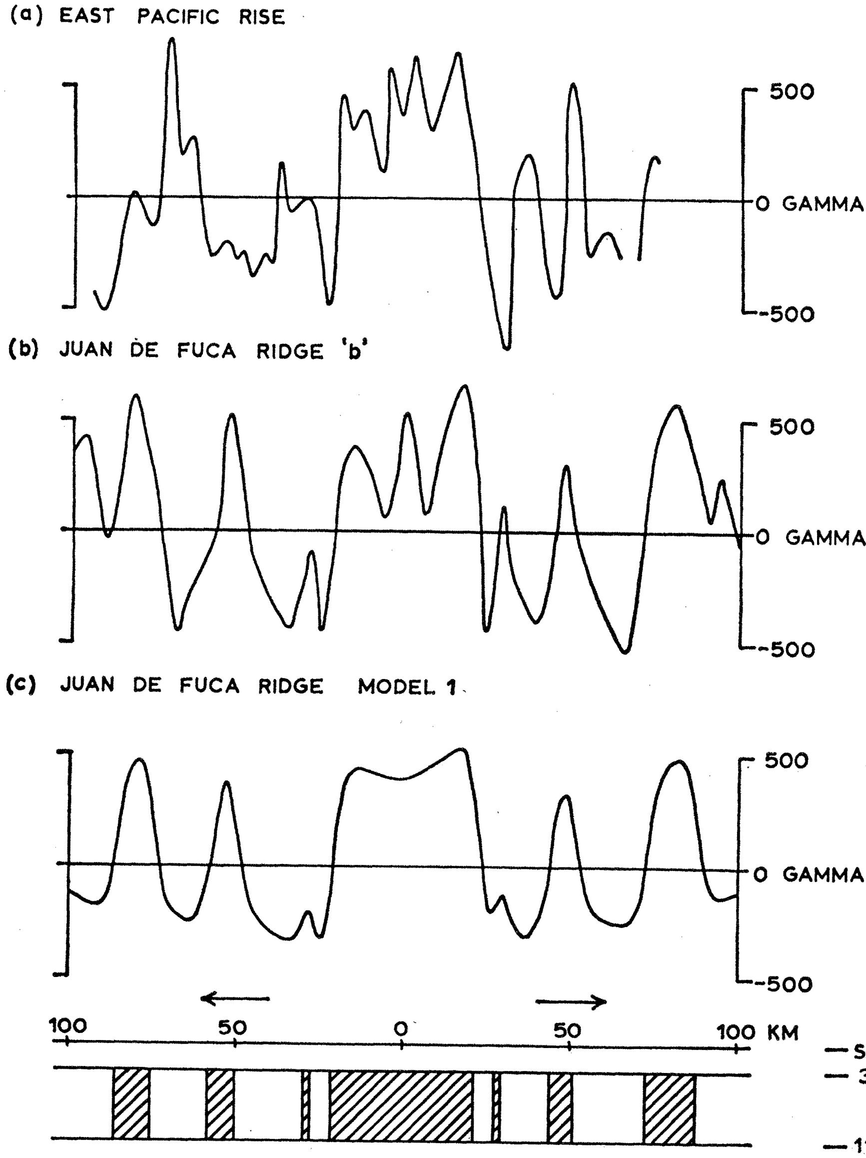

Fig. 2. (*a*) Observed profile across the East Pacific Rise at 59°S, 149°W (*16*). (*b*) Observed profile "b" across the Juan de Fuca Ridge (see Fig. 4). (*c*) Model and calculated anomaly for Juan de Fuca Ridge, assuming generalized crustal blocks (compare Fig. 1*c*).

fined entirely to layer 2. As previously, the central block is assumed to be more strongly magnetized because it is the only block composed exclusively of young material which is magnetized normally, except for the minor possibility of self-reversals. Volcanism probably occurs over a wider zone than the central block, and all other blocks will therefore be contaminated with younger material, often of reverse polarity to that of the initial block, and hence lowering or modifying its resultant magnetic effect. The serpentinite of layer 3 is almost certainly riddled with basaltic feeders for the flows and intrusives of layer 2. If these feeders are taken into account they will have the effect of slightly lowering the effective susceptibility assumed for layer 2 in Fig. 3*c*. This susceptibility is, as it stands, comparatively high but not unreasonable.

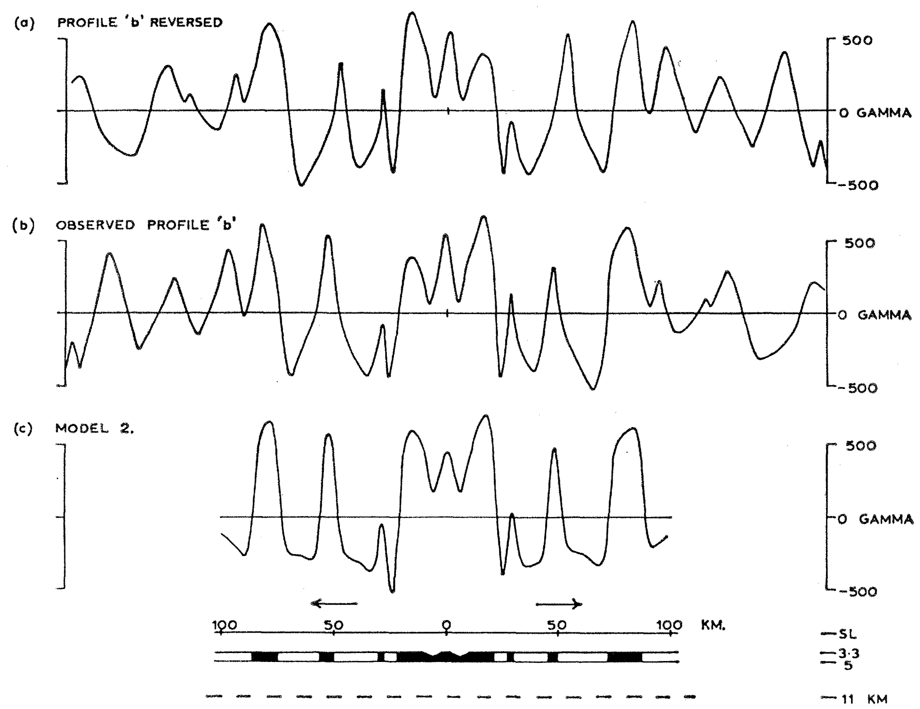

Fig. 3. (*a*) and (*b*) Observed profile "b" across the Juan de Fuca Ridge together with its mirror image about its midpoint, to demonstrate its symmetry. (*c*) Model and calculated anomaly for Juan de Fuca Ridge assuming a strongly magnetized basalt layer only. Black, normally magnetized material; unshaded material of this layer, reversely magnetized. Normal or reverse magnetization is with respect to an axial dipole vector; axial dipole dip taken as + 65°. Effective susceptibility taken as ± 0.01, except for the central block, + 0.02.

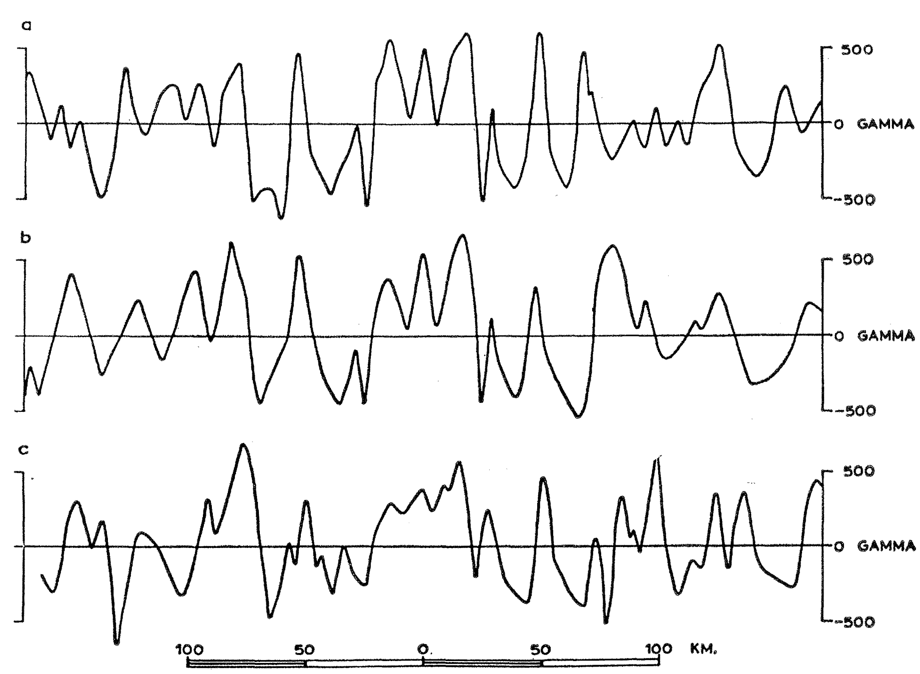

Fig. 4. Observed profiles "a," "b," and "c" at intervals of 45 km along Juan de Fuca Ridge, north to south. Midpoint of profile "b" is 46°39'N, 129°24'W. True bearing of profiles is 110°.

Comparison of Figs. 2*c* and 3*c* confirms that the essential feature of the Vine and Matthews hypothesis is the normal-reverse contacts; the actual distribution of magnetization within layers 2 and 3 of the oceanic crust is a matter of speculation at the present time (*2, 11*). However, the comparison also suggests that the second model is a considerable improvement on the first, despite the fact that it is still very simple. The original, generalized model of Vine and Matthews (Model 1) and the specific model after Hess (Model 2) have been chosen to illustrate what are possibly the two extremes, but it seems increasingly probable that the observed anomalies can best be reproduced by strongly magnetized, basaltic material in layer 2 and less strongly magnetized material at depth, whether this decrease in magnetization be due to a general increase in grain size, a change in rock type, or metamorphic effects.

A literal interpretation of the Vine and Matthews hypothesis implies that the magnetic anomalies observed over ridges at certain latitudes and orientations should be roughly symmetrical (for example, as in Fig. 1), but the simplicity of this model when compared with the probable complexity of the real situation makes a high degree of symmetry improbable. Iceland, although atypical in some ways, must give certain pointers as to the nature of the crestal province of the ridge system. Work on Iceland (*12*) suggests that the structure is symmetrical about the central rift or tension crack and has been formed by crustal drifting away from it. Although the rift is persistent, it seems likely that its location might change occasionally, and multiple cracks may occur, as is the case in the south of Iceland at present. Different conditions might prevail over different parts of the ridge system. Quiet, steady conditions of crustal emplacement and associated volcanism might produce a considerable degree of symmetry.

A surprisingly high degree of symmetry is exhibited by the Juan de Fuca Ridge (*8*). Three profiles across the ridge are shown in Fig. 4; they are at 45-km intervals along the ridge. In Fig. 3 the central profile is shown together with its mirror image to demonstrate the symmetry. This suggests a quiet growth for the ridge, and it is possibly significant that no active submarine volcanism has been reported from this area despite the fact that the ridge is presumed to be active because of the occurrence of recent earthquakes along the bounding transform faults (*8*). Symmetry of ridge profiles might be sought elsewhere. As with correlation of magnetic anomalies on adjacent profiles, the symmetry of the anomalies about the axis of a ridge is probably much less obvious from profiles than from a detailed survey.

It is becoming increasingly apparent that both the linearity of oceanic, magnetic anomalies and the steep gradients which bound them are obvious from a detailed magnetic survey but much more difficult to see from comparatively random profiles. Even the marked linearity of the anomalies over the Juan de Fuca Ridge is not necessarily obvious from adjacent profiles across it. Although profiles *a* and *b* in Fig. 4 correlate well, their correlation with profile *c* is not so good, and one might easily not anticipate the pronounced "grain" of the survey map (*1*). We should therefore like to reiterate the recent plea by Peter and Stewart (*1*) that magnetic surveys are of so much greater value than random profiles. Aeromagnetic surveys would appear to be perfectly adequate. It has been known for several years, but more convincingly established recently (*1, 11*), that the magnetic anomalies are, in general, quite unrelated to the bathymetry except over isolated seamounts or apparent transcurrent faults [all of which are, possibly, transform faults (9)].

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Radioactivity: Distribution from Cratering in Basalt

Abstract. *Samples of airborne and ground-deposited debris produced by an experiment in nuclear excavation were analyzed to determine the fate of various radioactive nuclides. A few tenths percent of the nonvolatile species and 10 to 20 percent of the volatile species escaped beyond the immediate vicinity of the crater.*

Suggested uses for nuclear excavation include the production of railroad cuts, mines, and harbors. Its first major use may be in constructing a new transisthmian canal. Very little information is available concerning the release of radioactivity, one of its most serious technical and political problems. The most relevant data come from the Danny Boy experiment at the Atomic Energy Commission's Nevada Test Site at 1015 hours P.S.T., 5 March 1962; ground zero was at 37°06′39.79″N, 116°21′53.82″W (*1*).

The Danny Boy event was an underground nuclear explosion designed to produce a crater in hard rock (basalt). A 0.43-kiloton device, detonated 33.5 m below the surface, formed a crater 18.9 m deep and 65.2 m in diameter (*2*). The cloud from the detonation grew rapidly to a width of about 900 m and a height of 300 m; after about 3 minutes growth was controlled primarily by ordinary atmospheric dispersion processes. At the time of detonation, winds were 22 km/hr from 168° azimuth at the surface and 50 km/hr from 190° 1100 m above ground. On 6 March there were wind gusts in the morning, with 1.22 cm of precipitation during the day (*2, 3*). Much of the total radioactivity produced was trapped in and below the

Table 1. Results of chemical analyses of samples from fallout trays, expressed as *J* values: disintegrations of nuclide *i*. J_i, disintegrations per minute (of nuclide *i*) per square meter, divided by the field reading in millirads per hour. In recording *J* values, the factor shown at the head of each column was omitted; to obtain original values, multiply each tabulation by the appropriate factor.

Station, distance* (m)	Field reading†	*J* value										
		Sr^{89} (10^5)	Sr^{90} (10^3)	Zr^{95} (10^5)	Mo^{99} (10^6)	Cs^{136} (10^4)	Cs^{137} (10^3)	Ba^{140} (10^6)	Ce^{141} (10^5)	Ce^{144} (10^4)	Nd^{147} (10^5)	Eu^{156} (10^4)
E-1, 762	48	1.9	2.2	1.4	5.8	6.3	3.7	2.9	8.1	3.5	5.3	2.3
T-17, 762	22	0.62	0.62	0.81	2.6	2.9	1.1	1.2	3.5	1.7	2.2	0.93
E-3, 1524	17	6.5	6.3	2.0	6.1	11	9.8	6.1	12	4.1	5.2	3
E-5, 2286	6	3.7	2.8	1.2	3.8	7.1	7.6	3.7	7.2	2.3	3.2	1.4
E-7, 3048	3	6.6	5.2	2.7	11	12	12	1	11	4.1	8.6	3.4
W-11, 3048	10	4.0	3.2	3.1	9.2	15	7.1	5.7	12	4.8	7.5	4.4
X-22, 5182	8	3.1	2.5	2.7	8.5	9.8	5.2	4.2	11	5.3	8.1	3.3
Y-20, 7620	0.6	3.9	2.2	0.73	2.7	3.5	9.7	2.5	4.5	1.5	2	1
Y-26, 7620	.4	0.22	0.29	.16	1.0	1.2	0.52	0.27	9.3	3.4	0.48	0.29
Average J_i		3.4	2.8	1.6	5.6	7.6	6.3	3.1	8.7	3.4	4.7	2.2

* From point of detonation. † Millirads per hour, 1500 hours 6 March.