APPENDIX.

A Report on Magnetic Disturbances in Northamptonshire and Leicestershire and their Relations to the Geological Structure.

By ARTHUR HUBERT COX, *M.Sc.*, *Ph.D.*, *F.G.S.*

(*Drawn up at the Request of the Iron-ore Committee of the Conjoint Board of Scientific Societies.*)

Received July 5, 1918.

[PLATES AP. 1–AP. 3.]

CONTENTS.

INTRODUCTION.

History of the Research.

DURING the course of the magnetic re-survey of the British Isles, recently carried out by Mr. G. W. WALKER under the auspices of the Royal Society, it was found that Melton Mowbray, Leicestershire, was a centre of pronounced magnetic disturbance, both vertical and horizontal. This result was in conformity with that obtained by RÜCKER and THORPE* in their surveys carried out 29 and 24 years earlier.

So far as is known the only element that gives rise to magnetic phenomena on a *large scale* is iron.† It appeared probable, therefore, that the local disturbances were to be connected with the distribution of iron in the rocks, and accordingly the origins of such disturbances were likely to be intimately related to the geological structure of the district.

The subject was brought to the notice of the Council of the Royal Society by Mr. WALKER, and was referred by the Council to the Conjoint Board of Scientific Societies, who appointed a Committee to consider the bearing of magnetic disturbances on the possible occurrence of iron-ores.

* 'Phil. Trans.,' Ser. A, vol. 181 (1890), p. 288; and vol. 188 (1896), pp. 602 and 626.

† The fact that there exist substances, as, for example, cobalt, nickel, and the Heusler alloys—CuAlMn—that contain no iron and yet are, or can be rendered, strongly magnetic, has not been overlooked. It has also been claimed that magnetism may be induced in certain minerals, such as kyanite Al_2SiO_5, dolomite $CaMg(CO_3)_2$, and leucite $KAlSiO_3$, but it has not been satisfactorily proved that in these latter cases no trace of iron is present. In any case the susceptibilities of such mineral substances are small as compared with those of materials containing an appreciable amount of iron, and are not sufficient to excite the disturbances measured by Mr. WALKER. The whole results of this work go to show that the disturbing element must be iron in some form or other.

If the magnetic disturbances were, as was reasonable to suppose, due to the local distribution of iron, it became important to ascertain in what form and quantity this iron was present.

It is well known that although iron is the only element capable of showing magnetic phenomena on a large scale, yet the magnetic influence exerted by a given weight of it is dependent on the particular state of combination of the iron. In the metallic state iron is, or can be rendered, very strongly magnetic, but its susceptibility is rapidly diminished by the presence of small amounts of certain substances, notably manganese.* In the combined state as magnetite (Fe_3O_4) it is still strongly magnetic, although not nearly so strongly as would be the corresponding amount of iron in the free state. In the case of magnetic pyrites (Fe_3S_4) the susceptibility sinks considerably below the value for magnetite itself, and in the case of other compounds of iron the susceptibility is still further diminished, so that hæmatite, for example, is ordinarily spoken of as non-magnetic. Definite examples are given later (p. 84 *et seq.*, and p. 105). *In general, it may be said that iron in the ferrous condition has a much greater magnetic susceptibility than the corresponding amount of iron in the ferric state.*

It follows that although magnetic disturbances are in all probability connected with the distribution of iron in some form or other, yet *the amount of disturbance will not be a direct measure of the amount of iron present.* A rock containing a small percentage of iron in the form of magnetite (Fe_3O_4) will exert a much greater effect than a rock containing a large percentage of iron in the form of hæmatite (Fe_2O_3). Further, magnetite will continue to exert a disturbing influence even when disseminated through a large amount of material of low susceptibility, as in the case of the magnetite of igneous rocks. In general, a number of magnetic observations at different points round the disturbing centre are necessary before the effects due to deep-seated rocks of high susceptibility can be distinguished from those due to rocks of low susceptibility situated nearer the surface. A magnetic disturbance, therefore, does not necessarily imply the presence of iron in a form economically workable.

Melton Mowbray is only one of a number of centres of magnetic disturbance, but it is of importance as being partly surrounded by an iron-ore producing country. The ore-bearing strata occur in the form of a flat sheet capping a ridge of high ground which makes a crescent round the town, the inner diameter of the crescent being about six miles. Within the crescent the sheet has disappeared as the result of denudation. The observation-stations in the magnetic surveys by RÜCKER and THORPE, and by Mr. WALKER, were situated about four miles from the outcrop of the iron-ores, and in rocks below their horizon. The importance of determining

* Sir R. HADFIELD, C. CHENEVEAU, and CH. GENEAU, 'Roy. Soc. Proc.,' Ser. A, vol. 94 (1917), p. 65.

whether the observed magnetic disturbances are connected in this case with the ore deposits now being worked is obvious.

It was accordingly decided by the Iron-ore Committee (1) that a detailed magnetic survey of the Melton Mowbray district should be undertaken; (2) that at the same time a geological examination of the district should be made; and (3) that the rocks collected in the district should be tested for their magnetic susceptibilities, with a view to determining the origin of the local magnetic disturbances, and to ascertain their connexion, if any, with the distribution of the known iron-ore deposits. The magnetic survey was undertaken by Mr. WALKER with the aid of a grant from the Royal Society. The geological aspect of the question was placed in the hands of Dr. AUBREY STRAHAN, Director of the Geological Survey, who obtained the sanction of H.M. Treasury for the employment of Dr. A. H. COX as a temporary member of the staff of the Geological Survey in order that he might carry out the geological part of the work. The work of determining the magnetic susceptibilities of the various rocks collected was undertaken by Prof. ERNEST WILSON, of University of London, King's College.

The geological examination of the district was greatly facilitated by the fact that the whole area had recently been re-surveyed by the officers of H.M. Geological Survey, and the results of their investigations shown on the Geological Maps and Memoirs (list on p. 94).

It was thought desirable that a series of observations should also be made on some known sheet of iron-ore with a view to determining the character of the disturbances caused by the sheet. The district selected on the advice of Prof. H. LOUIS, the Chairman of the Committee, was near Irthlingborough in Northamptonshire. This district was chosen as being the largest sheet of unworked ferrous carbonate known to him suitable for the experiment, as its boundaries had been determined with great accuracy. It is now being opened out by the Ebbw Vale Iron Company. Accordingly a series of similar observations was made in that district also by Mr. WALKER, Dr. COX, and Prof. WILSON. During this examination the most valuable assistance and information were received from Mr. THOS. FALCON, Manager of the Ebbw Vale Company's iron-mines at Irthlingborough, and it is desired to take this opportunity of expressing our great indebtedness to him for the facilities so freely granted.

Method of Procedure.

It should be borne in mind that the disturbances to be measured were exceedingly small as compared with those set up by some of the ore-deposits in Sweden,* where

* For an account of the procedure adopted in Sweden, see "The Most Prominent Features of Swedish Iron-ore Mining," by G. NORDENSTRÖM, 'Journ. Iron and Steel Inst.,' 1898, p. 35; also "On the Location and Examination of Magnetic Ore Deposits by Magnetometric Measurements," by EUGENE HAANEL, Ottawa, Canada, 1904.

the magnetic method of surveying iron-ore bodies is well known. The procedure, therefore, was not so simple as that adopted for the Swedish cases, where magnetite occurs in great masses at or near the surface, resulting in disturbances which approach in order of magnitude the normal effect of the earth's magnetic field.

The general positions of the magnetic observation-stations were chosen (1) round Irthlingborough, with the help of Mr. THOS. FALCON, with due regard to the outcrop and distribution of those rock-strata that, in view of their iron-content, might be expected to exert a disturbing influence; (2) round Melton Mowbray, in order that by means of a system of triangulation it should be possible to gain some idea of the distribution and depth of origin of the local disturbing forces. The geographical positions and azimuths of the observation-points were accurately fixed by Mr. GIBSON, Chief Observer of the Ordnance Survey, whose services were kindly lent for the occasion by Colonel Sir CHARLES CLOSE, Director General of the Ordnance Survey. The field magnetic observations were made concurrently by Mr. WALKER. After the control magnetic data from Greenwich had been obtained from the Astronomer Royal, and the other necessary data from the Ordnance Survey Office, the reduction of the observations was completed and the disturbing forces calculated.

A geological examination of each district was then made by Dr. COX. Specimens of the typical rocks, and of any other rocks which by reason of their exceptional characters appear likely to shed light on the problem, were sent to Prof. ERNEST WILSON, who determined their magnetic susceptibilities. By these means it was possible to ascertain the rocks which were in any way capable of exciting the magnetic disturbances, and those which were certainly incapable of causing the disturbances. The results so obtained were compared with information derived from a chemical and petrological examination of the most susceptible rocks, and the geological structure was then considered in its bearing on the known facts.

In the following pages, Mr. WALKER and Prof. WILSON give separate accounts of their own parts in the investigation, and Dr. COX has endeavoured, in Part III., with the help of contributions from Mr. WALKER, to show how far the results may be explained by the known geological structure. Contributions from Mr. WALKER or Prof. WILSON included in Part III. are indicated by quotation marks and initials.

Dr. COX wishes to acknowledge his great indebtedness to Dr. STRAHAN, Director of the Geological Survey, for much valuable advice as to the carrying out of the work, and for his help in the preparation of this report. He has also to thank other officers of the Geological Survey, more especially Dr. H. H. THOMAS and Dr. WALCOTT GIBSON, for their assistance in obtaining specimens and for help on various points. He is also indebted to Prof. WATTS, Secretary of the Committee, for reading the manuscript and for many helpful suggestions as well as for the loan of certain specimens of Charnwood Forest rocks. Finally, he has to offer his thanks to Dr. RONALD BURROWS, Principal of King's College, London, to Prof. Sir HERBERT JACKSON, and to his colleagues in the Chemical Department of King's College, for

allowing him special facilities and enabling him to obtain the requisite time for carrying out his part of the research.

PART I.—THE MAGNETIC OBSERVATIONS.

By G. W. WALKER, F.R.S.

The observational part of the detailed magnetic survey recommended by the Iron-ore Committee was carried out in August and September, 1917. Observations were obtained at five points round Irthlingborough, and at ten points within the triangle of which Melton Mowbray, Loughborough, and Nottingham form the corners; while at Melton and Loughborough (which were stations in the General Magnetic Survey of 1914–15) observations were repeated as a control.

We are under great obligations to the Director-General of the Ordnance Survey for sending his chief observer to mark and fix the stations, and to the Astronomer Royal for control magnetic data from Greenwich.

The field data are entered in the observation books of the General Magnetic Survey, which are preserved by the Royal Society for future reference. The procedure of reduction has been exactly the same as in the General Survey, and the disturbing forces were obtained by deducting from the observed values, the magnetic forces which characterise the British Isles as a whole. The latter in Leicestershire are approximately, North = 17,200γ, West = 4,850γ, Vertical = 44,000γ.

The unit of measurement is denoted by "γ," which is 0·00001 (or 10^{-5}) of a Gauss or dyne. It should be kept in mind that in field work (even under the favourable conditions afforded by a limited area) we cannot depend on the horizontal component being correct to nearer than 10γ or the vertical component to nearer than 30γ. I quite believe the errors are often less, but we cannot be sure by this method of observation.

The datum plane from which disturbances are reckoned is by no means precisely known, and in any case the disturbances may contain "district" effect, by which I mean effect common to an area comprising perhaps several counties as distinct from effects only parochial in extent. For exploring purposes it is thus convenient to consider "relative" disturbances of stations, and these are obtained by deducting the mean effect for the stations concerned. I have calculated these and charted them, but I wish to make clear that this is merely an artifice intended to give a clue to the cause of the disturbances.

The disturbing forces are tabulated in two sets, viz.: (1) Irthlingborough series, and (2) Melton series.

(1) *The Irthlingborough Series.*—The points (A to E) were chosen to secure as much variation as seemed possible, and Mr. FALCON, manager at Irthlingborough, gave me great help in choosing them. E was to be near the edge of the bed, A and

B to be well on the top of the bed, C to be entirely off the bed, and D to be on the continuation of the bed on the south side of the valley.

The accompanying geological map (Plate Ap. 1) shows the positions of the stations and their "relative" disturbing forces. The horizontal disturbance is shown in magnitude and direction by an arrow drawn from the station, the scale being 1 cm. = 10γ. The vertical disturbance is shown by a number at the station, + for a downward effect, − for an upward.

The relative disturbances are by no means great, but the most pronounced features are the comparatively large upward disturbance at E, and the horizontal disturbance towards the south at B.

The mean disturbance common to the five stations does not directly concern us, but it is to be noted that it is in close agreement with the disturbance obtained in the general survey for the district, of which Northamptonshire forms a part.

Disturbing Forces.

—	North.	West.	Vertical.
Irthlingborough, A	−56	+19	−34
" B	−78	+30	−62
" C	−30	+12	−45
" D	−24	+20	−73
" E	−24	+5	−109
Mean disturbing force	−42	+17	−65

(A − sign for a disturbance to North or West denotes that the disturbance is South or East respectively.)

Subtracting the mean in each case, the relative disturbing forces are :—

—	North.	West.	Vertical.
A	−14	+2	+31
B	−36	+13	+3
C	+12	−5	+20
D	+18	+3	−8
E	+18	−12	−44

The results are discussed in a later section (p. 87).

(2) We pass now to the *Leicestershire Series*. The positions of the observation stations and the "relative" disturbing forces are indicated on the coloured geological map (Plate Ap. 3), the arrows showing the direction of horizontal disturbance being drawn to a scale of 1 cm. = 40γ.

As already stated, observations were made at Melton and Loughborough which were stations in the General Magnetic Survey of 1914–15.

Duly corrected to epoch—January 1, 1915—the values at Loughborough were:—

	H.	D.	I.
General Magnetic Survey, 1915 .	17,920	15° 24′·8	67° 50′·8
Observations in 1917	17,916	15° 30′·0	67° 51′·4

giving disturbing forces:—

	N.	W.	V.
1915	+34	−137	−39
1917	+23	−110	−27

The values at Melton similarly corrected to epoch were:—

	H.	D.	I.
1915	18,036	16° 29′·0	67° 49′·5
1917	*18,003*	*16° 30′·5*	*67° 48′·3*

giving disturbing forces:—

	N.	W.	V.
1915	+14	+265	+238
1917	−20	+264	+149

Observations made in 1917 at the new and old stations gave the following results:—

DISTURBING FORCES.

—	North.	West.	Vertical.
Asfordby	−121	− 51	+ 37
Waltham	−113	+ 22	− 74
Seagrave	− 10	− 30	− 13
Melton	− 20	+264	+149
Broughton	− 72	+ 14	+ 53
Penhill	+ 7	+ 67	+118
Keyworth	− 12	+ 14	+ 74
Berryhill	− 34	− 7	+ 87
Plumtree	− 32	− 29	+ 50
Barton	− 2	− 45	+ 31
Rempstone	−120	− 32	+230
Loughborough	+ 23	−110	− 27
Mean disturbing force . .	− 42	+ 6	+ 60

Subtracting the mean in each case we get the

RELATIVE Disturbing Forces.

—	North.	West.	Vertical.
Asfordby	−79	− 57	− 23
Waltham	−71	+ 16	−134
Seagrave	+32	− 36	− 73
Melton	+22	+258	+ 89
Broughton	−30	+ 8	− 7
Penhill	+49	+ 61	+ 58
Keyworth	+30	+ 8	+ 14
Berryhill	+ 8	− 13	+ 27
Plumtree	+10	− 35	− 10
Barton	+40	− 51	+ 29
Rempstone	− 78	− 38	+170
Loughborough	+65	−116	− 87

Observations made at neighbouring stations during the General Magnetic Survey in 1914–15, and corrected to epoch January 1, 1915 :—

Nottingham	+38	− 17	+230
Or relative	+80	− 23	+170
Coalville	+42	−101	+ 30
Or relative	+84	−107	− 30 about 3½ miles W.S.W. of Loughborough.

Thus the interferences drawn from the General Magnetic Survey are substantially confirmed. I am not surprised by the discrepancy in D at Loughborough because the General Survey observations there were made, as it turned out, during a magnetic storm of considerable violence. But the comparatively large drop of 33 in H at Melton (which accounts for the drop of 100γ in V) appears to me too large to be accounted for by observational error, although it is true that the recent observation at Melton was made during a very high wind with intermittent thunder and heavy rain.

Notwithstanding this drop Melton still remains a point of large westerly disturbance and large downward disturbance.

That the large disturbances at Melton and Loughborough are not directly due to one and the same centre of disturbance is shown by the distribution of the forces at the intermediate points Asfordby and Seagrave.

The system of disturbing forces is evidently a somewhat complicated one and admits of several interpretations, so that additional observations appear necessary to make the problem more definite. Meanwhile attention may be directed to the essential features :—that Melton, Rempstone, Nottingham, and in a slighter degree Pen Hill, are maxima of downward disturbance, and therefore in the vicinity of what RÜCKER called "magnetic peaks." Taking into account the distribution of the vertical and of the horizontal disturbing forces, the presence of a pronounced line of disturbing matter running nearly east and west from Melton to between Rempstone and Loughborough is indicated.

RÜCKER and THORPE* have pointed out that the disturbing forces may be due either to permanent or to induced magnetisation of the rocks. It appears from their work that in many cases the hypothesis of induced magnetism is consistent with the observations, but that there are cases in which a minor portion of the effect may be due to permanent magnetism.

On the hypothesis that the disturbing forces are due to the earth's normal field acting by induction on the rocks, it is better to avoid elaborate calculation and to have a simple if only approximate rule to guide one in looking at the map. The following rule, which can be justified analytically, I have found useful as a rough test. The number expressing the disturbing force is given in units 10^{-5} of an absolute unit of force, and similarly it is convenient to use a unit 10^{-5} of an absolute unit to express the susceptibility of the rocks. The rule is that the number giving the observed disturbance which we wish to explain, is an approximate measure of the lowest susceptibility by which we could hope to provide a quantitative explanation. Thus, if the disturbance is 100, then 100 is the order of magnitude of the minimum susceptibility which a rock must possess if it is to account for that particular disturbance. The actual minimum value possible for the susceptibility might be somewhat less than 100, perhaps even as low as 70, but a rock with a susceptibility of only 50 would, in general, have to be ruled out as a possible cause for a disturbance measured by 100. Moreover, if the rock attains only this minimum susceptibility, its upper limit will have to be situated close up to the surface of the ground, and it would have to extend in depth and area to distances determined by the disturbances at neighbouring stations, granting that the disturbances at adjoining stations have the same cause.

My general inference from the forces at Rempstone and Melton Mowbray with their neighbouring stations is that there are two main magnetic centres situated along the line running westwards from Melton Mowbray which has been particularised above, and that the depth of these can hardly be less than 1 km. (say 3000 feet), while it may be as much as 2 or 3 km.

As already indicated further observations are necessary in order to get precise information as to the distribution of the disturbing magnetic material. This raises a point of some importance. Absolute observations do not give the most accurate results and in any case take too long. If further details are to be carried out, I think it will be necessary to prepare a set of portable variometers on the principle

* 'Phil. Trans.,' Ser. A, vol. 181 (1890), p. 314.

of that which I designed and tested in the Irish Magnetic Survey of 1915 for horizontal forces. With such instruments more accurate observations can be obtained, and moreover, it might be possible to observe about six stations per day instead of one as at present.

PART II.—ON THE MAGNETIC SUSCEPTIBILITY OF CERTAIN ROCK SPECIMENS.

By Prof. ERNEST WILSON, *King's College, London.*

The magnetic permeability μ of a substance is given by the ratio of B, the magnetic induction, to H the magnetising force. The magnetic susceptibility κ is related to the permeability μ by the expression

$$\mu = 1 + 4\pi\kappa.$$

The susceptibility as above defined refers to unit volume, and is sometimes called the volume-susceptibility to distinguish it from the mass-susceptibility obtained by dividing it by the density.

A special instrument was devised capable of measuring quickly susceptibilities of a low order of magnitude, and certain of the results so obtained were compared with those obtained by the ordinary magnetometer method.

For use with the new instrument of balance the specimens have a length of 4 cm. or less, and in most cases an approximately circular cross-section of 1 cm. diameter. In other cases, the cross-section has been approximately square and 1 cm. in the side. For the magnetometer tests the specimens had a length of about 10 cm. and approximately square cross-section of 1·5 cm. in the side. When using the balance the magnetic force is applied transversely, and with the magnetometer it is applied longitudinally. In the first case the magnetic force in C.G.S. units (H) varies from about 6·7 to 300; and in the second the variation is from about 33 to 100. The susceptibility of any *one specimen* has been found to be practically constant between these limits.

The following table* gives the description of and locality of the specimens examined. The volume susceptibility of each specimen is given in C.G.S. units, together with the corresponding magnetising force H employed at the time of test.

In one or two cases where confirmation seemed desirable, specimens have been re-tested; for example, the basalt E. 6520.* The specimen L. 63 as originally tested

* In the table and throughout this paper L. denotes a specimen collected in connection with the Leicestershire observations; N. one in connection with the Northamptonshire observations; E. specimens belonging to the collection of the Geological Survey at the Museum of Practical Geology.

Rocks from the Melton Mowbray and Irthlingborough Districts.

Summary of Magnetic Properties.

Specimen No.	Description and locality.	Weight of specimen.	Density.	Magnetising force H in C.G.S. units.	Volume-susceptibility in 10^{-5} C.G.S. units. Individual values.	Average value.	Reference page.
	I. Igneous Rocks. *Dolerites*, intrusive in Coal Measure Strata.	gr.					
E. 6519	Dolerite, marginal portion, bore-hole, Owthorpe, Nottinghamshire	3·843	2·660	49·5	434	434	101, 108, 113 and 128
	Re-tested after demagnetisation	—	—	22 40	495 449	472	
E. 6520	Dolerite, central portion, bore-hole, Owthorpe, Nottinghamshire	6·295	2·760	132 248	8·8 8·9	8·8	
	Re-tested	—	—	237	10·3	10·3	
L. 114	Dolerite, coal shaft, Whitwick, Leicestershire	8·386	2·890	24 39 24	338 405 430	391	
	Re-tested after demagnetisation	—	—	23 39	380 437	408	
E. 8987	Dolerite, bore-hole, Kelham, Nottinghamshire, after demagnetisation	7·885	2·65	19·8	279	279	
L. 115	Dolerite, lower portion, bore-hole, Southwell, Nottinghamshire	7·455	2·830	46	210	210	
E. 11444	Basalt, upper portion, Southwell, Nottinghamshire	5·295	2·58	56 48	7·2 6·6	6·9	
	Basalt, Lava in Carboniferous Limestone.						
L. 113	Amygdaloidal basalt (loadstone), Bakewell, Derbyshire	6·295	2·610	40 69 40 69	11·8 11·9 12·9 13·4	12·5	103, 107, 125
	Granites, and Associated Rocks, Mount Sorrel, Leicestershire.						
L. 15	Normal granite, grey variety, Mount Sorrel quarry	9·008	2·630	96 69 47	69·5 62·9 62·9	65	102, 107, 125 and 131
	Re-tested	—	—	48 73 73	59·2 60·1 60·1	60	
	(Another specimen)	by magn	etometer	—	—	130	
L. 15A	Granite, grey variety, Mount Sorrel quarry, matrix surrounding heathen	5·167	2·663	98 47	134 131	132	
L. 16A	Granite, pink variety, Mount Sorrel quarry, matrix surrounding heathen	11·618	2·660	67	45	45	
L. 015A	"Heathen," or basic patch in L. 15A	6·635	2·697	67 47	181 181	181	
L. 016A	"Heathen,"* or basic patch in L. 16A	10·400	2·660	47	40	40	

* The specimen included a small amount of normal pink granite.

ROCKS from the Melton Mowbray and Irthlingborough Districts (continued).

Summary of Magnetic Properties (continued).

Specimen No.	Description and locality.	Weight of specimen.	Density.	Magnetising force H in C.G.S. units.	Volume-susceptibility in 10^{-5} C.G.S. units. Individual values.	Volume-susceptibility in 10^{-5} C.G.S. units. Average value.	Reference page.
	I. IGNEOUS ROCKS (continued).	gr.					
L. 100	Basic granite, marginal, Brazil Wood	8·025	2·780	124	22	22	
				157	23		
L. 101	Hornblende-diorite, Brazil Wood .	9·205	2·810	156	11·6	12	
				200	12·1		
L. 103	Basic dyke in granite, Mount Sorrel	8·610	2·770	50	74	80	
				80	85		
	Basic Dykes, intrusive in Cambrian Rocks.						
L. 110	Camptonite, intrusive in Hartshill quartzite, Nuneaton	4·908	2·640	128	20	21	103, 107, 125 and 134
				483	21		
				483	22		
	Charnwood Forest Rocks.						
L. 13	Augite-granophyre ("syenite"), Groby Quarry	6·284	2·710	200	4·1	4	102, 106, 125 and 134
				335	4·0		
				440	3·95		
L. 10	Basic granophyre ("greenstone"), Newhurst Wood	9·650	2·980	137	7·95	8·2	
				241	8·4		
L. 6	Porphyroid (dacite), High Sharpley	8·200	2·660	230	1·2	1·3	
				556	1·4		
	II. IRON ORES.						
	(A) *Northampton Sands, Irthlingborough District.*						
	Green Carbonate Ores, unoxidised, from underground workings.						
99	Chalybite, massive crystalline (inserted for comparison)	12·182	3·720	47	55·5	59	
				82	62·8		
N. 89	Sandy oolitic ore, No. 2 pit, Irthlingborough tunnel	10·275	2·340	66	20·9	22	88 *et seq.* 105
				90	23·4		
N. 91	Compact oolitic ore, No. 2 pit, Irthlingborough tunnel	13·845	3·110	100	28	28	
N. 88	Partially oxidised oolitic ore, No. 2 pit, Irthlingborough tunnel	4·981	2·770	200	29·6	29	
				100	29·4		
				67	28·2		
				44	28·6		
	(A second specimen)	7·860	2·770	196	34·7	32	
				97	30·6		
				47	30·7		
	(A third specimen)	by magn	etometer	—	—	30	
N. 90	Fine-grained silicate ore, No. 2 pit, Irthlingborough tunnel	13·645	3·290	50	35·8	36	
				98	37·3		
	Brown Limonite Ores, oxidized, from surface outcrop.						
N. 82	Sandy oolitic ore, Clarke's pit, near Rushden	10·721	2·210	197	8·3	8·3	
N. 83	Compact concretionary "boxstone," Barlow's Pit, Finsdon	by magn	etometer	64	—	6	

Rocks from the Melton Mowbray and Irthlingborough Districts (continued).

Summary of Magnetic Properties (continued).

Specimen No.	Description and locality.	Weight of specimen.	Density.	Magnetising Force H in C.G.S. units.	Volume-susceptibility in 10^{-5} C.G.S. units. Individual values.	Volume-susceptibility in 10^{-5} C.G.S. units. Average value.	Reference page.
	II. Iron Ores (continued).	gr.					
	(B) *Limonite Ores from Marlstone, Melton Mowbray District.*						
L. 71	Fine-grained concretionary ore, quarry south of White Lodge, near Eastwell	5·677	2·640	96 200 300	9·9 9·2 10·4	10	97, 104 and 110
	(A second specimen)	7·567	2·580	247 196	10·5 10·5	10·5	
L. 63	Oolitic ore, Wartnaby.	8·49	2·250	200 98	20·7 21·4	21	
	Re-tested after being reduced to circular cross-section	5·670	2·670	92 180	20·6 26·2	23	
	(Another specimen).	by magnetometer		—	—	30	
L. 70	Ferruginous limestone, "Sandrock," Wartnaby	6·010	2·420	385 587	2·2 2·2	2·2	
	Hæmatite (inserted for comparison)	16·56	4·91	160 97	22·1 21·9	22	
	(C) *Clay Ironstones from Coal Measures.*						
L. 19	Clay-ironstone concretion, lower Coal Measures, New Stanton, Derbyshire	13·825	3·335	86 108	32·4 36·9	34·5	98, 104 and 127
L. 28	Clay-ironstone, fire-clays, Cossall brick pit, Erewash Valley, Nottinghamshire	11·612	2·930	48 92	20·6 22·6	21·5	
	Ankerite, film on coal (inserted for comparison)	4·555	2·52	158 101	10·8 9·7	10	
	III. Limestones and Dolomites.						
L. 58	Compact limestone, "Cement-stones," Lower Lias, Barrow-on-Soar, Leicestershire	12·145	2·640	515 300	0·38 0·38	0·38	97 and 103
L. 37	Dolomite, Magnesian Limestone, Bulwell, Nottinghamshire	8·610	2·650	605	0·18	0·18	104 and 125
L. 111	Dolomite, fine-grained, Carboniferous Limestone, Cloud Hill, Leicestershire	9·320	2·780	603	0·47	0·47	
	IV. Clays and Slates.						
N. 78	Blue clay, Upper Lias, No. 1 Pit, Irthlingborough	8·305	1·84 ?	94 250 375	2·0 1·9 2·0	2	88 and 104
L. 9	Blue slate, Swithland Slates, Woodhouse Eaves, Charnwood Forest	8·200	2·780	245 355	3·9 3·9	3·9	104
L. 102	Hornfels, contact-altered slate, Brazil Wood, near Mount Sorrel	7·785	2·740	242 332	3·3 3·2	3·2	
L. 112	Hornfels, contact-altered slate, Brazil Wood, near Mount Sorrel	6·700	2·810	240 237	6·4 5·9	6·1	

had a square cross-section, and gave the comparatively high susceptibility 21×10^{-5}. After being reduced to a circular cross-section and its density re-determined, the value of the susceptibility was found to be 23×10^{-5}.

In other cases the specimens were re-tested "after demagnetisation," for the following reason. It is well known that if a piece of iron be subjected to a considerable magnetising force, and afterwards tested for permeability at lower forces, the permeability then found is smaller than would have been the case had the specimen been first demagnetised. The complete previous magnetic history of rocks is unknown, but some of them, owing to their retentivity, show that they must have acquired a high degree of magnetisation at some past time. By subjecting such a specimen to an alternating magnetic force, gradually diminishing to vanishing point, the magnetic effects, due to this retentivity, which have perhaps existed for centuries, can be removed in a few minutes, and it is then found that the specimen (for example the Dolerite, E. 6519*) may have increased susceptibility.

Experiments have been made which prove that the method is applicable to powders, thus making it possible to deal with magnetic permeability of fair average samples obtained, if necessary, from relatively large areas. The powders are placed in a glass tube of known internal volume, and by taking into account the specific gravity and total weight of the powder in the tube, the measure of concentration is obtained, and results comparable with those of the same material in the solid state can be readily secured.

Emphasis should be laid upon the fact that samples cut from the same hand-specimen frequently show widely different susceptibilities, as illustrated by the Mount Sorrel granite (L. 15). The only satisfactory way in which to obtain an average result is to test a large number of specimens of the same rock.

It may be observed that when a rock is spoken of as having a high susceptibility, as for example in the dolerites, the susceptibility-value is in reality exceedingly small as compared with the susceptibility of such a material as iron in which the susceptibility may have a maximum value of $40,000,000 \times 10^{-5}$ in C.G.S. units.

My best thanks are due to E. F. Herroun, Esq., F.I.C., for the use of his magnetometer and for his valuable assistance.

PART III.—THE GEOLOGICAL STRUCTURE AND THE MAGNETIC DISTURBANCES.

(A). NORTHAMPTONSHIRE: IRTHLINGBOROUGH DISTRICT.

The investigations in this district had for their special object the testing of the changes in the character of the disturbances caused by a flat sheet of iron-ore according as the observations were made in positions above the sheet, along its edges, and outside its edges.

* See footnote, p. 83.

I. The Geology of the District.

The geological structure is simple so far as the surface Formations are concerned.* The succession among the strata that actually crop out on the surface is as follows :—

			Thickness.
Glacial .	Boulder clay . .	Stony clay	Covering up to 50 feet thick on the high ground.
Jurassic .	Great Oolite series	Limestones and blue clays .	Up to 30 feet.
	Estuarine beds . .	Vari-coloured sands and blue and grey clays with limestone bands.	15–20 feet.
	Northamptonshire iron-ore.	Oolitic iron-ores, green carbonates and red oxides of iron, the upper and lower portions are ferruginous sandstones.	14–18 feet.
	Upper Lias . . .	Blue clays.	180 feet.

The distribution of the various beds is shown on the map (Plate 1), and the sequence and structure are illustrated by the section (fig. 1), which is taken along the line of the tunnel at present in course of construction by the Ebbw Vale Co.† The strata are seen to lie almost horizontally, but there is locally some gentle folding, and occasionally some minor faulting.

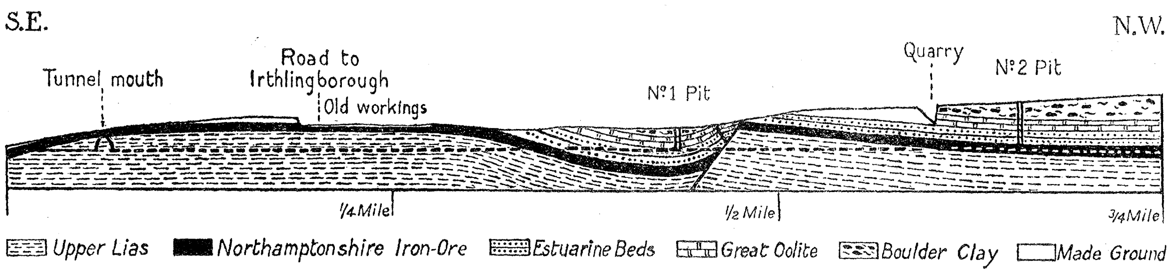


Fig. 1. Section along line of tunnel west of Irthlingborough.

The Upper Lias clays form a floor to the whole district and are only seen in the valleys. The Great Oolite series gives rise to a plateau averaging 270 to 300 feet

* Geological Survey Map: Sheet 52 (1 inch old series).

† The section was reduced from a large-scale section kindly supplied by Mr. Thos. Falcon, Manager of the Iron Mines.

above O.D. The plateau is dissected by wide valleys with gently sloping sides and flat alluvial bottoms excavated in the Upper Lias clays.

Although the valley slopes are gentle, the ore-bed, which is readily permeable by water, has a great tendency to slide down over the underlying impervious Lias clays into the valleys. This large-scale sliding may introduce complications into observations taken along the edges of the sheet.

Under the plateau, where the bed is covered up to a depth of 50 feet or more by impermeable clays of the Estuarine and Great Oolite series, the ore is mainly in the form of ferrous carbonate with some ferrous silicate. Along the surface outcrops the ore is completely oxidised to limonite. In intermediate positions the oxidation is still going on along the highly irregular jointing. With low barometric pressure such large volumes of CO_2 are evolved from the rocks that workmen have to be withdrawn from the tunnels at present being driven through the deposit.

There is a great difference in susceptibility between the oxidised and unoxidised portions of the ore, the latter giving, as would be expected, the higher values, as shown by the following figures (*vide* pp. 85 and 105):—

—	—		Volume-Susceptibility.*	Iron content.*	
				FeO.	Fe_2O_3.
				Per cent.	Per cent.
N. 83	Brown oxidised ore from the outcrop . .		6×10^{-5}	—	77·28
N. 82	,, ,, ,, ,, . .		8×10^{-5}	—	44·76
N. 89	Green sandy carbonate . .	from underground workings.	22×10^{-5}	40·68	4·32
N. 91	,, carbonate	from underground workings.	28×10^{-5}	38·54	0·31
N. 88	,, brown carbonate . .	from underground workings.	32×10^{-5}	36·96	12·00
N. 90	,, silicate	from underground workings.	36×10^{-5}	49·32	0·80

(E.W. and A.H.C.)

Thus in general the outcrops of the sheet will be composed of less magnetic material than the more deeply buried portions. Even for these parts, however, the susceptibilities are low, less than half that of the Mount Sorrel granite.

In view of the differences in the susceptibility of different parts of the sheet, the positions of the observation stations are important (*see* figs. 2 and 3). Two of the stations, A and B, are on the Great Oolite plateau well above the ore-bed. A is about in the centre of the plateau and almost exactly 100 feet above the ore, while B is near the eastern edge of the plateau and also about 100 feet above the ore. One station E is situated on the valley side and actually on the outcrop of the iron-ore. At this point, however, the usual slipping has taken place so that the thickness of the ore is

* The figures in each case refer to the air-dried specimen.

reduced to four feet. E is thus very near but not quite on the edge of the outcrop. The fourth station C is on the valley alluvium below the iron-ore outcrop, while the

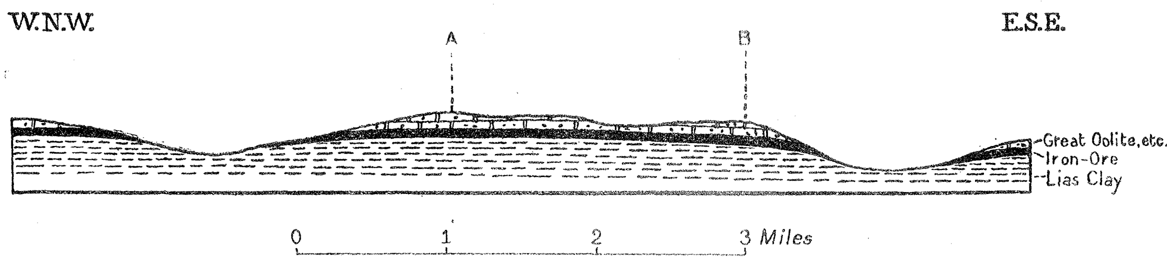


Fig. 2.

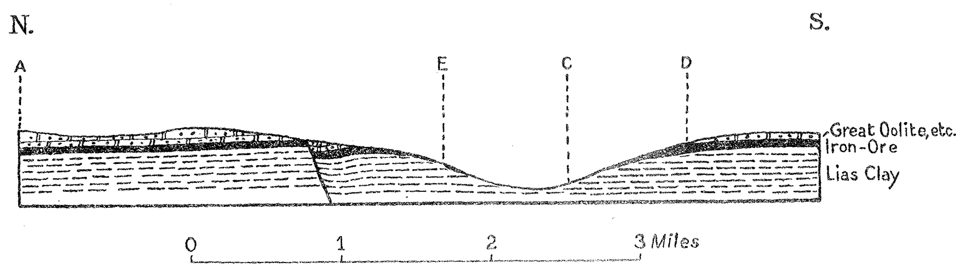


Fig. 3.

Figs. 2 and 3. Sections to illustrate geological structure of Irthlingborough district.

fifth station D is on the opposite side of the valley and on the iron-ore bed, the depth of the bed at this point being unknown.

II. Interpretation of the Results.

The figures for the various observation-stations have been given in an earlier section (p. 79). Regarding their correlation, Mr. Walker writes as follows :—

"The ironstone bed may, I understand, be regarded as a flat sheet of ferrous carbonate, considerably oxidised at the outcrop. The material is very slightly susceptible and may be expected to be magnetised by the earth's induction so that the upper side has south magnetism."—G.W.W.

"The adjoining diagram (fig. 4) illustrates the lines of force in a vertical section through such a flat plate. If we are above the line XY the horizontal force always tends to the centre of the plate. In magnitude it is small near the centre, rises to a maximum as we get just over the edge, and beyond the edge diminishes again to zero. The vertical disturbance is relatively downwards near the centre, diminishes to zero as we approach the edge and then changes sign to an upward disturbance, attains a maximum and then rapidly diminishes."—G.W.W.

"If we compare this with the map, it will be seen that the relative disturbances at A, B, and E are exactly what we should expect from the flat sheet, and we may even argue that the edge runs a little to the north of E, a little to the north of B, and rather more to the north of A."—G.W.W.

"The effects at C and D are perhaps not so clearly related to the southward extension of the iron-ore sheet. The outcrop follows, however, a rather irregular course on the south side of the valley, and this may introduce complications in the local disturbances. Further, it must be kept in mind that, owing to experimental error and uncertainty as to the datum-plane, there might be superposed a force of a magnitude sufficient to reduce C to zero and, as it happens, the same force would also be sufficient to reduce D to an extremely small horizontal disturbance and a slightly greater upward disturbance."—G.W.W.

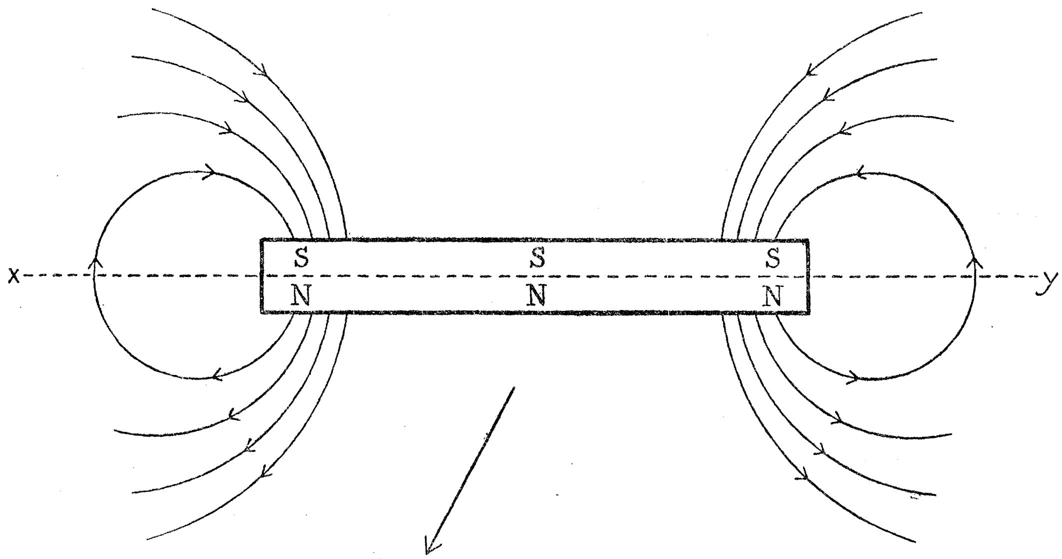


Fig. 4. Section to illustrate distribution of lines of force arising from a horizontal sheet magnetised by earth's induction.

"On the other hand, even if a force that would reduce C to zero were superposed on the forces as determined, the effects at the points A, B, and E would not be modified in essential features. At A the horizontal disturbance to the south would be increased, while the downward vertical disturbance would be reduced. At B the small + vertical disturbance would be converted into a − vertical disturbance, but the big horizontal disturbance, the characteristic feature at B, would still remain and its value would be slightly increased. At E the horizontal disturbance would be reduced, while the − vertical disturbance, the characteristic feature would be increased."—G.W.W.

"Thus the observations at three of the stations—A, B, and E—agree with the results to be expected from the geological structure, while the results at two stations—C and D—are inconclusive, perhaps owing to the irregular nature of the outcrop in their vicinity. Applying the rough guide from the susceptibilities of the rocks (see p. 82), there is harmony between the observed forces, the known geology and the measured susceptibility of the rocks. It thus appears highly probable that the known ironstone is the *vera causa* of the observed forces."—

G.W.W.

"The observations show that with improved differential instruments, such as those referred to on pp. 82 and 83, it would be possible to map the distribution of even comparatively weak magnetic material."—G.W.W.

III. The Underground Structure.

It will be shown in the second part of this section dealing with the Melton Mowbray district, that the disturbances there do not arise from strata near the surface, but that they are deep-seated in origin and closely connected with faulting. It is necessary to consider, therefore, whether the same may not be true for the Irthlingborough district, where a fault is also present, and whether the agreement between the disturbances and the results to be inferred from a consideration of the surface geology may not be entirely fortuitous.

On this point the magnetic observations themselves shed some light. Mr. Walker states:—

"The system of disturbances suggests as the most obvious distribution of disturbing magnetic material a flat sheet with a boundary as already indicated (p. 90), and situated at no great depth."—G.W.W.

Now within the first few hundred feet of strata we know of no rock other than the ironstones likely to cause such disturbances. This is apparent from the following considerations. The Northampton Ironstones and associated rocks belong to the Jurassic System. The divisions which immediately underlie the ironstone are the Upper, Middle, and Lower Lias. The Upper Lias, as already mentioned (p. 88), consists of stiff blue clays attaining, in the Irthlingborough district, a thickness of about 180 feet. The susceptibility of these clays has been tested (p. 86) and is so small as to be negligible. Below the Upper Lias is the Middle Lias. This division contains an important ironstone bed in Leicestershire (see part B of this section, p. 97), but southwards from Leicestershire the ironstone bed thins out, as shown by borings, and eastward "beyond Wellingborough the rock bed, where it can be recognised at all, is merely a layer of pebbles from a few inches to a foot thick."* Such a bed obviously could not cause the disturbances measured. Below this attenuated representative of the Middle Lias is the Lower Lias consisting entirely of blue clays with some limestone bands. The susceptibility of both clays and limestones is negligible. The thickness of this formation beneath Irthlingborough is probably at least 450, and perhaps as much as 600 feet, which would bring its lower limit down to between 400 and 500 feet below O.D., that is to about 700 feet below the Northampton Ironstone. *Throughout this thickness of 700 feet, it is practically certain that there is no rock that can give rise to distinct magnetic disturbances.*

As to what rocks come immediately beneath the Lower Lias clays our information is not so definite, for, unfortunately, there is no deep boring in the immediate vicinity of

* Beeby Thompson, Article on "Northamptonshire," 'Geology in the Field,' 1910, vol. II., p. 460.

Irthlingborough. The nearest deep boring in fact is at Orton,* about 15 miles N.N.W. of Irthlingborough. There the Lower Lias was about 620 feet thick, and its base was reached at −292 O.D., below which were 49 feet of Rhætic and other beds down to −341 O.D. Then came an igneous rock which was pierced to a depth of 74 feet before the boring was abandoned. This rock compared closely, according to Prof. BONNEY,† with the porphyroids or altered andesites (dacites) of High Sharpley, Charnwood Forest. The buried Charnian Ridge of Pre-Cambrian rocks therefore rises at Orton to within 341 feet of O.D. The ridge probably trends south-eastward, that is towards Irthlingborough, following the usual Charnian strike, N.W. to S.E., but whether its depth beneath the surface remains constant in that direction remains unknown, as the Palæozoic floor has not been reached for a considerable distance either east or south-east from Orton.‡

Below the level of −500 O.D., therefore, Charnian rocks *may* well occur, and with them may be associated igneous rocks that *might* produce disturbances. But all this is purely speculative. Actually the Charnian rocks may lie much below the level of −500 O.D., and there may be no associated igneous rocks of a kind to give rise to disturbances. The igneous rocks in the Charnian of Leicestershire all have small susceptibilities, with the single exception of the Mount Sorrel granite. The important point is that we can reasonably predict that for at least 700 feet below the Northampton Ironstone there exists no rocks capable of producing any marked magnetic disturbances.

As to the *physical possibility* of the disturbances arising at depths greater than 700 feet, Mr. WALKER states :—" The evidence from the lines of force is not absolutely definite in view of possible errors of observation. But it is at least sufficient to show that such a depth of origin is unlikely. The numbers given by station E suggest that the origin could not be deeper than even 300 feet without complications appearing in the results given by stations A and B. Further, even if the disturbances do originate so low as, or lower than, 700 feet below the surface, the rock stratum causing the disturbances would have to be such that its shape and boundaries corresponded with those observed at the surface. Such a coincidence is extremely unlikely."—G.W.W.

IV. SUMMARY.

The evidence so far obtained is in favour of the disturbances originating in the iron-ore bed itself, and consequently their agreement with results to be expected from the surface geology indicates a real and not a chance relation between the disturbances and the geological structure.

If further work should tend to confirm this agreement between magnetic disturbances and geological structure, it might open out the possibility of mapping

* H. J. EUNSEN, " Palæozoic Rocks beneath Northampton," 'Q. J. G. S.,' vol. XL. (1884), p. 491.

† *Op. cit.*

‡ See A. STRAHAN, "Pres. Address," 'Q. J. G. S.,' vol. LXIX. (1913), pl. A, p. lxxviii.

deposits of material that is only feebly magnetic, providing that the geological structure is not too complicated. But in all such cases due regard would have to be paid to the possibility, and indeed in many cases the probability, of other and perhaps larger deep-seated disturbances being added to those arising at comparatively shallow levels.

Accordingly it may prove important, or even essential, to work out the details of disturbances caused by deep-seated rocks, possibly of little or no economic value, in order to obtain a measure of the factors superimposed by them on disturbances due to deposits of economic importance, the distribution of which it is required to ascertain. The results obtained in Leicestershire, which are discussed in the following section, furnish an example.

(B). LEICESTERSHIRE: MELTON MOWBRAY DISTRICT.

I. THE GEOLOGICAL SEQUENCE AND STRUCTURE.

The district here described embraces the triangle between the towns of Melton Mowbray, Nottingham, and Leicester. It was necessary for the geological examination to embrace a wider region, since older rocks, such as may be present deep underground beneath Melton Mowbray on the east, actually crop out at the surface further west.

The geology of the district is illustrated by the New Series of 1-inch Geological Maps, and by the accompanying explanatory Memoirs issued by H.M. Geological Survey.* The information in these Memoirs has been largely drawn upon during the compilation of the following account of the geology of the district.

1. THE GENERAL SUCCESSION.

The Formations that occur at the surface, or that may occur underground (within the area over which the magnetic observations were made), are :—

Recent . . . . Alluvium . . . . . . Clays, sands, and gravels in river-valleys.

Unconformity.

* 1. "The Geology of the Country between Atherstone and Charnwood Forest," by C. FOX-STRANGWAYS and W. W. WATTS, 'Mem. Geol. Survey,' 1902, and Sheet 155, 1-inch Geological Map (New Series); "The Geology of the Country between Derby . . . . and Loughborough," by C. FOX-STRANGWAYS and W. W. WATTS, 1905, and Sheet 141; "The Geology of the Leicestershire and South Derbyshire Coalfield," by C. FOX-STRANGWAYS, 1907; "The Geology of the . . . . Derbyshire and Nottinghamshire Coalfield," by W. GIBSON, 1908, and Sheet 125; "The Geology of the Country between Newark and Nottingham," by G. W. LAMPLUGH, W. GIBSON, and others, 1908, and Sheet 126; "The Geology of the Melton Mowbray District," by G. W. LAMPLUGH, W. GIBSON, and others, 1909, and Sheet 142; "The Geology of the Country around Nottingham," by G. W. LAMPLUGH, W. GIBSON, and others, 1910, and Nottingham District Sheet; "The Concealed Coalfield of Yorkshire and Nottinghamshire," by WALCOTT GIBSON, 1913.

				Thickness. Feet.	
	Glacial		Boulder clay, &c.		Thick sheet of stony clay of irregular distribution, mainly developed on the higher ground, with glacial sands along the river valleys.
	Unconformity.				
Mesozoic	Inferior Oolite	Inferior Oolite Limestone		26	only developed in extreme east of the district.
		Estuarine beds	Variable sands and clays	26	
		Northampton Sands	Iron-ores and ferruginous sands	24	
	Lias	Upper Lias	Blue clays	120	
		Middle Lias: Marlstone	Oolitic iron-ores and ferruginous calcareous sandstones	7–14	
		Middle Lias: Clays		100–120	
		Lower Lias	Blue clays with thin limestone bands	670	
	Trias	Rhætic	Calcareous shales with thin bands of nodular limestone	30–40	
		Keuper Marl	Red and green marls with thin bands of gypsum, and of calcareous sandstone	630	
		Waterstones	Red sandstones	0–120	only developed in north-western part of district.
		Bunter Beds	Red sandstones and pebble-beds	0–400	
	Unconformity.				
Palæozoic	Permian		Red marls and dolomitic limestones	0–60	
	Unconformity.				
	Carboniferous	Coal Measures	Shales, fire-clays, clay-ironstones, sandstones, and coal-seams	0–5000	
		Millstone Grit	Massive sandstones and shales	0–740 (not exposed at surface, but proved in a boring).	
		Carboniferous Limestone	Limestones, dolomitic limestones and shales	(Not exposed at the surface nor proved in bore-holes.)	

No rocks belonging to any Palæozoic Formation below the Carboniferous crop out at the surface, nor have any such rocks been as yet proved underground.

	Unconformity.				
Pre-Cambrian		Charnian	Slates, ashes, and agglomerates	Great thickness.	

In addition to the stratified rocks enumerated above, the following igneous rocks are known to occur :—

Upper Carboniferous or later . .	Olivine-dolerites . . .	Intrusive in the Coal Measures, as dykes, sills, laccolites, or fault-intrusions.
Pre-Carboniferous	Granites	Intrusive into Charnian rocks (Mount Sorrel).
Pre-Cambrian	Granophyres of acid and basic types	Intrusive into Charnian rocks.
,, ,, ...	Andesites and dacites .	Intrusive and ? as lavas in Charnian rocks.

The greater part of the surface is occupied by various rock-groups of the Mesozoic Formations. They rest one upon the other in regular sheets, which dip, as a rule, gently eastward or south-eastward, so that newer rocks successively appear in that direction. Some of the sheets are, however, more or less lenticular in character and may wedge out and disappear altogether owing to overlap, thus complicating estimations as to the depth of the underlying formations.

The Palæozoic and older Formations come to the surface from beneath the Mesozoic rocks only in the western part of the district. Though the Palæozoic (Carboniferous) rocks also dip eastwards as a general rule, between them and the Mesozoic Formations there is a strong unconformity, and the dips of the various Palæozoic rocks are not nearly so regular as, and are, as a rule, steeper than, those of the Mesozoic Formations above them.

It will therefore be readily understood that the structure of the district, so far as the deep-seated rocks are concerned, is in part still unknown, and that it is not always possible to say definitely on what Formation the Mesozoic rocks rest.

For these reasons it will be convenient to begin the description of the strata with the higher beds, the geographical distribution of which is definitely known.

Both Palæozoic and Mesozoic rocks are affected by a system of east—west to south-east—north-west faulting. The distribution of this faulting, which has proved to have a definite relation to the distribution of the magnetic disturbances, will be discussed later (p. 111).

2. Rocks above the Coal Measures.

(a) *Formations above the Marlstone Iron-ore.*

For our present purpose the Formations above the Marlstone (Middle Lias) Iron-ore may be dismissed with a brief reference. Apart from the Boulder Clay there is nowhere any cover to the iron-ore except at the extreme eastern margin of the district where the Marlstone is covered by the Upper Lias Clays, blue clays attaining a thickness of 120 feet. Throughout this thickness there is no ferruginous bed which could cause any magnetic disturbance. Above the Upper Lias there is at one locality, around Waltham, a thin representative of the Northamptonshire Iron-ore, covered by a few feet of sands and Inferior Oolite Limestone. The Northamptonshire Iron-ore round Waltham is limited to a patch of country measuring about $2\frac{1}{2}$ miles in each direction. Judging by the effect of the same rock at Irthlingborough, where oxidised at the surface (see p. 89), the few feet of ironstone in this small patch of country cannot give rise to the large magnetic disturbances noticeable at Rempstone, 14 miles away to the west.

(b) *The Marlstone Iron-ores.*

The Marlstone Ironstone of the Middle Lias represents an altered oolitic limestone in which the original calcium carbonate has been replaced by ferrous carbonate which was subsequently oxidised to the hydrated ferric oxide limonite. The bed is extensively worked along many parts of the outcrop, and in some localities has been entirely removed. The iron-ore itself is from 7 to 14 feet thick, and it rests upon 15 to 20 feet of ferruginous limestones and calcareous sandstones—the so-called "Sandrock." The strata are practically horizontal and they stand out from the softer clays below, giving rise to a ridge of high ground. This ridge sweeps round the town of Melton Mowbray in a crescent, breached at one or two points by valleys. The inner diameter of the crescent is about six miles. Despite the wide outcrop of these iron-ores, they cannot be held responsible for the magnetic disturbances, for reasons to be given later (p. 110).

(c) *Formations below the Marlstone Iron-ore and above the Coal Measures.*

Below the Marlstone iron-ore with its accompanying ferruginous sandstones lie the Middle Lias Clays, measuring from 100 to 120 feet thick. Below them comes the Lower Lias, composed of blue clays with thin limestone bands, the division having a total thickness of 670 feet. Throughout the clays there is, in the district now under consideration, no important ferruginous band. Only in the north-east of the district does there appear a band of ferruginous limestone, seldom exceeding a foot in thickness, which is the local representative of the important Lincolnshire iron-ores.

Below the Lower Lias are the Rhætic beds, 30 to 40 feet of shales with thin limestones, and below them the Keuper Marl, red and green marls with a few bands of gypsum and numerous bands of calcareous sandstone or "skerry." This Formation attains here a thickness of about 630 feet.

Below the Keuper Marl in the area around Nottingham, is a considerable thickness of sandstones, namely the Waterstones and the Bunter Beds, the two sandstone formations together attaining a maximum thickness of 500 feet. The sandstones are underlain by about 60 feet of red marls and dolomitic limestones belonging to the Permian system.

In all the 1800 to 1900 feet of strata just described as occurring below the Marlstone there is no single bed that could give rise to any magnetic disturbance.

3. The Deep-seated Geology.

(d) *The Distribution of the Coal Measures.*

The divisions last mentioned—the Permian, Bunter, and Waterstones—thin out and disappear one after another when followed south-eastwards from Nottingham, with the result that the Keuper Marls eventually come to rest directly and with strong unconformity upon older formations.

Where the succession is most nearly complete the Permian is underlain by the Coal Measures, a thick series of shales, fireclays, coals, and sandstones, with numerous thin bands of clay-ironstones.

The Measures themselves crop out west of Nottingham, forming the southern termination of the "visible" portion of the Nottingham and Yorkshire coalfield. Eastwards from Nottingham they are everywhere concealed by newer rocks, but have been reached by deep borings, with the result that a great extension of the Coalfield has been proved to exist underground, forming what is known as the "concealed coalfield."

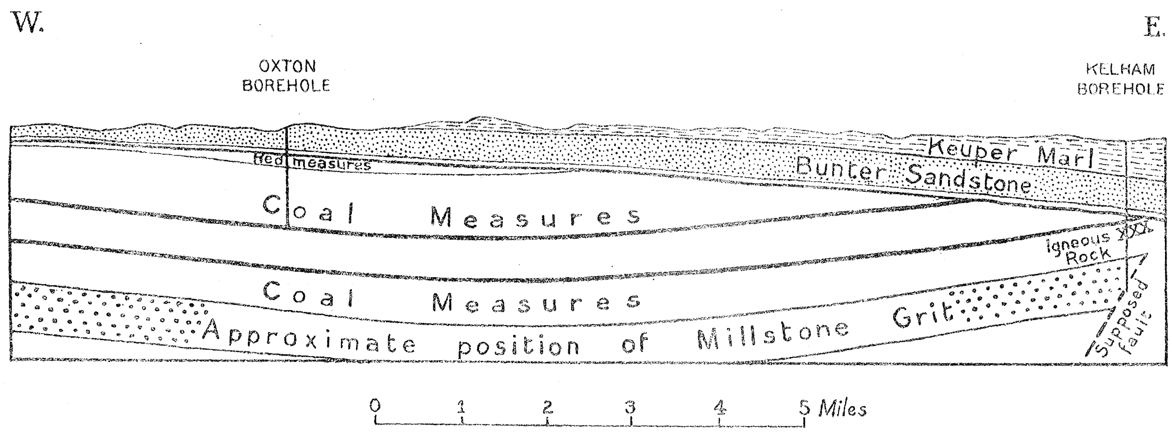


Fig. 5. Section to show structure of "concealed" coalfield of Nottinghamshire.*

Details of the bores and references are given by Dr. Walcott Gibson in his account of this concealed coalfield† and in various other Memoirs of the Geological Survey.† It is sufficient here to mention the borings at Kelham, near Newark, and

* I am indebted to Sir Aubrey Strahan for permission to copy (with slight modification) this section from "The Search for New Coalfields in England," 'Lecture to the Royal Institution of Great Britain,' March 17, 1916.

† See footnote on p. 94 for list of Memoirs.

Owthorpe, Edwalton, and Ruddington, all about 12 or 15 miles towards the north-west of Melton Mowbray. The Coal Measures were found at only −467 feet O.D. at Ruddington, at −604 O.D. at Edwalton, and at −869 O.D. at Owthorpe. A comparison of the strata traversed shows that the prevailing easterly dip is still maintained.

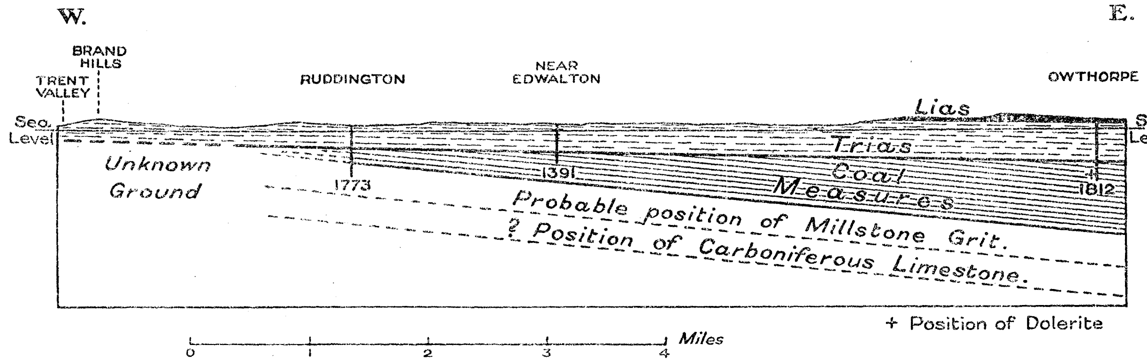


Fig. 6. Section through southern portion of "concealed" coalfield of Nottinghamshire.

Thus the Coal Measures extend at least as far south as Ruddington under a comparatively thin cover of Mesozoic Rocks. Further, the available evidence points to an extension of the same beds to Melton Mowbray. Dr. W. Gibson writes:— "From the estimated depth of the Alton coal at the three points (Ruddington, −972 feet; Edwalton, −2200 feet; and Owthorpe, −3400 feet O.D.) we may deduce that the strike of the Carboniferous rocks is roughly N. 30° W. If this direction is maintained to the south-east, the Coal Measures should be present over the whole area east of a line joining Ruddington and Melton Mowbray . . . . ."*

As regards the country some distance west of Melton Mowbray, it is known that the Coal Measures are absent in a part at least of the Soar Valley, where Triassic rocks rest directly on Pre-Cambrian rocks. But how far eastwards towards Melton these relations hold is not known.

(e) *Rocks Older than the Coal Measures.*

Below the Coal Measures come in normal sequence the *Millstone Grit*, a great thickness of massive sandstones, grits, and shales. Their presence within part of this district is proved by the Ruddington boring which entered the beds at −1030 feet O.D., and penetrated them for 742 feet without reaching their base.

In normal sequence the Millstone Grit is underlain by the *Carboniferous Limestone*, a thick series of limestones and dolomitic limestones and shales. How far this Formation is developed beneath the Melton Mowbray district is quite uncertain. On the north-west side of Charnwood Forest it crops out at Grace Dieu, near

* "The Geology of the Melton Mowbray District," 'Mem. Geol. Survey,' 1909, p. 10.

Whitwick, and it was pierced in a bore-hole at Northampton,* 35 miles south of Melton Mowbray.

The next Formation that might be present is the *Silurian.* Some calcareous mudstones and limestones touched in a boring at Hathern, in the Soar Valley, have been thought to be possibly of Silurian age. †

The possibility that *Cambrian rocks* are present must be considered, though they nowhere outcrop at the surface of the district in question, nor have they been proved by bore-holes, which, as a rule, naturally cease before Cambrian rocks could be entered. But it must not be forgotten that at Nuneaton, Cambrian rocks, with associated intrusive igneous rocks (camptonites), directly underlie the Coal Measures. Further Cambrian rocks have been proved in a boring at Leicester, ‡ 15 miles south-west of Melton Mowbray, where they were found underlying Trias at 837 feet below the surface. To the west of Leicester, Cambrian rocks, with associated igneous intrusions, have been pierced at various points near Market Bosworth.§ More recently Cambrian shales, again with intrusive rocks, have been found directly to underlie the Lower Lias at Calvert, Buckinghamshire, at a depth of only 480 feet.‖ Thus the Cambrian strata with their associated intrusions evidently have a considerable underground range in the eastern Midlands.

The oldest rocks seen are the *Pre-Cambrian rocks* (Charnian), which crop out at the surface in Charnwood Forest, where they appear directly from beneath the Keuper Marl or Sandstone. They consist of a thick series of ashes, agglomerates, and slates, with abundant associated igneous rocks of various kinds, the majority intrusive, but some perhaps extrusive. The Charnian ridge strikes north-west—south-east, and although sinking under the Trias, it evidently continues in a south-eastern direction for a considerable distance under comparatively shallow cover. This is proved by the fact that the Charnian rocks were pierced in a boring at Orton, Northants (see p. 93), while igneous rocks of a type common in Charnwood Forest actually appear at the surface at Croft, and at various other points in South Leicestershire.

To the north-east, however, the plane of junction between the Charnian rocks and the overlying Trias is very irregular, and it often dives rapidly underground, so that the Charnian rocks soon become buried beneath a considerable cover. Therefore

* H. J. EUNSON, "Palæozoic Rocks beneath Northampton," 'Q. J. G. S.,' vol. XI. (1884), pp. 484 and 495.

† The cores from this boring, put down in 1876, were unfortunately never inspected by any geologist who was able to leave a satisfactory record, so that the results are entirely lost. (See "The Geology of Burton . . . and Loughborough," 'Mem. Geol. Survey,' 1905, p. 54.)

‡ "The Geology of Leicester," 'Mem. Geol. Survey,' 1903, p. 63.

§ "The Geology of Leicestershire and South Derbyshire Coalfield," 'Mem. Geol. Survey,' 1907, p. 344.

‖ A. MORLEY DAVIES and J. PRINGLE, "Deep Borings at Calvert Station . . . ," 'Q. J. G. S.,' vol. LXIX. (1913), p. 308.

towards Melton Mowbray, 10 miles from the outermost visible Charnian strike-line, these older rocks are probably buried under at least 1000–3000 feet of newer strata.

4. The Igneous Rocks.

(f) *Dolerites Intrusive into the Coal Measures.*

No intrusive dolerites are present in the visible outcrop of the Coal Measures of the Yorkshire and Nottinghamshire Coalfield, but in the concealed portion of the coalfield several dolerites have been proved through the medium of deep borings.

One of these intrusions occurs in the central part of the area under consideration. It was penetrated by the Owthorpe boring at a depth of 1743 feet below O.D. Where pierced by the bore-hole the rock was only 40 feet thick.* Further north two other examples have also been met in bores through the Coal Measures. One of these is at Kelham near Newark, where a thickness of 77 feet of dolerite was proved between 1715 and 1792 feet below O.D.† The other is near Southwell,‡ about seven miles E.N.E. of Newark.

In the west of the district a dolerite has been pierced by a number of shafts near Whitwick in the Leicestershire coalfield. This rock occurs over an area of about $3\frac{1}{2}$ miles by 1 mile, and varies from 15 to 81 feet in thickness. It rests upon the upturned edges of the Coal Measures, but it is said not to alter the Triassic rocks above.§

In other parts of the country the frequent association of intrusive basic rocks with Coal Measure strata is well known. It is only necessary to mention the intrusions at Rowley Regis, Walsall, &c., in the South Staffordshire Coalfield,|| at the Clee Hills in Shropshire, and elsewhere. Similar dolerites are occasionally intrusive into lower horizons of the Carboniferous Rocks. They are found for example in the Millstone Grit, and in the Carboniferous Limestone of Shropshire,¶ and in the Lower Carboniferous Rocks of Scotland.

It has not yet been established whether these intrusions are of pre-Triassic age or younger, but the question is not of great importance so far as this investigation is concerned, for despite the wide outcrop of the Mesozoic rocks in the Midlands, and although their underground extension has been well explored by borings and deep wells, the only intrusion known to occur in them is the one at Butterton,

* "The Geology of Newark and Nottingham," 'Mem. Geol. Survey,' 1908, p. 106.

† "The Concealed Coalfield of Yorkshire and Nottinghamshire," 'Mem. Geol. Survey,' 1913, p. 58; also A. Strahan, 'Lecture to Royal Institution of Great Britain,' March 17, 1916, p. 6.

‡ The details of this boring have not at present been made public. I am indebted to Dr. Walcott Gibson for information as to the occurrence of the intrusive rock.

§ "The Geology of the Leicestershire and South Derbyshire Coalfield," 'Mem. Geol. Survey,' 1907, p. 33.

|| W. W. Watts, "Geology of the Birmingham District," 'Proc. Geol. Assoc.,' vol. XV. (1898), p. 397.

¶ W. W. Watts, "Geology of South Shropshire," 'Proc. Geol. Assoc.,' vol. XIII. (1894), p. 343.

North Staffs. This rock carries nepheline, which has not so far been proved to occur in the intrusions among the English Coal Measures, so that it may belong to a quite different series of intrusions. Since no other basic rock is known to occur in the Mesozoic rocks of the Midlands, we are warranted in assuming the probable absence of any basic intrusions in the Triassic and Jurassic rocks of the Melton Mowbray district. Accordingly we must look to the Coal Measures or older Formations for occurrences of these igneous rocks.

(g) *The Mount Sorrel Granite and Associated Rocks.*

The Mount Sorrel Granite represents the only granite intrusion which is exposed within the district described in this report, or for a considerable distance in any direction outside. It is largely covered by an unaltered mantle of Triassic Rocks so that its limits beneath the mantle are not known, but it is obviously of considerable extent. The granite is intrusive into Charnian Rocks, but it is not affected by the north-west—south-east (Charnian) movement which influences all the Charnian rocks. The granite is, therefore, presumably of much later date than the pre-Cambrian Charnian rocks. In no part of the country, however, is there any similar granite in Carboniferous or newer rocks, so that its age is almost certainly pre-Carboniferous. Petrologically it resembles most closely the "Newer" or post-Silurian granites of Scotland.* If it should be of the same age as the "Newer" granites of Scotland no stress could be laid on its apparently isolated nature, since any granite of corresponding age could not occur in Carboniferous or newer rocks. But such granites are very common in the Highlands, and they appear in the Southern Uplands, in the Cheviots, and in the Lake district. Thence southward there is no opportunity of seeing any similar granite until Charnwood Forest is reached, but buried intrusions may well occur. Thus the Mount Sorrel intrusion may not in reality be as isolated as it appears, and there may possibly be other granites in the district buried beneath the Triassic or Carboniferous rocks.

(h) *The Charnian Igneous Rocks.*

Igneous rocks of several types are of frequent occurrence in the Charnian Rocks. The majority, if not all, are intrusive in character. Among those that are always definitely intrusive are *granophyres* of varying acidity. They occur abundantly, sometimes in large masses a mile or more across. Their exact limits are often difficult to determine on account of the overlying Triassic Rocks, but they have evidently a wide distribution as they are seen at intervals from the north of Leicestershire to the south before they finally disappear beneath the newer rocks.

Porphyroids, or altered andesitic rocks, are also common as large intrusions, and possibly in some cases as lavas. They attain a great development in the north-western part of Charnwood Forest, while similar rocks have been proved by a deep

* W. W. WATTS, "Charnwood Forest," 'Geology in the Field,' vol. II., 1910, p. 777.

boring to occur under a cover of newer rocks as far away as Orton, Northants (see p. 93), 25 miles south-east of the Forest, so that they also appear to have a wide distribution.

(i) *Other Igneous Rocks Possibly Present.*

Besides the various rocks described above which are *known* to occur in the district, there may be other types of igneous rocks concealed underground, and although such other rocks have nowhere been *proved* within the limits of the district, yet their possible presence needs to be taken into account, and it is desirable to enquire as to the likelihood of their occurrence.

The Possibility of Basalts as Lava-flows in the Carboniferous Limestone.—It has already been mentioned (p. 99) that there is a likelihood of the Carboniferous Limestone occurring in its normal position below the Millstone Grit. This being so, it is desirable to enquire into the possibility of its including basalt lavas. Such lavas are extensively developed at the base of the Lower Carboniferous in the Midland Valley of Scotland, and are of local occurrence in Northumberland, Derbyshire, and Somersetshire, but in no other parts of England. But in the outcrops of Carboniferous Limestone nearest to Melton Mowbray—the small patches at Breedon Cloud, &c., north of Charnwood Forest—there are no lavas present, although the strata are on the same horizon as those that in Derbyshire contain the basalt flows.* Accordingly, the chances are that, if the Carboniferous Limestone is developed under the Melton Mowbray area, basalt lavas are not present.

"*Camptonites*" *of the type Intrusive into Cambrian Rocks.*—The possibility of Cambrian Rocks occurring deep underground in parts of the district has already been mentioned (p. 100). If such Cambrian rocks are present they probably contain sills of camptonite similar to those that are so abundant in the Cambrian strata of Nuneaton. The latter have been proved by boreholes† to extend over a considerable distance between Nuneaton and Charnwood Forest. No Cambrian Rocks have, however, been *proved* on the east side of Charnwood Forest. The age of the intrusions is not known, but it is significant that in this country they are never found in strata newer than the Cambrian.

II. The Relative Magnetic Susceptibilities of the Rocks.

1. The Sedimentary Rocks.

(a) *Non-Ferruginous and Slightly Ferruginous Rocks.*

Those rocks in which the iron-content is so small as to be negligible were found, whatever their nature, to have susceptibilities of a very low order of magnitude, as illustrated by the fine-grained limestones (cement-stones) of the Lower Lias and

* L. M. Parsons, "The Carboniferous Limestone bordering the Leicestershire Coalfield," 'Proc. Geol. Soc.,' No. 1004, March, 1917, p. 56.

† "The Geology of the Leicestershire . . . . Coalfield," 'Mem. Geol. Survey,' 1907.

by the dolomites from the Carboniferous Limestone and the Permian, with susceptibilities 0·38, 0·48, and 0·18* respectively.

As soon as iron in any form appears in a rock the susceptibility rises, as instanced by the ferruginous sandy limestone from the Marlstone with a susceptibility 4·3, the iron being present as limonite.

Similarly, in those clays or slates, the blue colour of which testifies to the presence of a certain amount of iron as pyrites and chlorite respectively, the susceptibility is slightly increased as seen from the figures for the Upper Lias Clay and for Charnwood Slates, 2·0 and 3·9 respectively. A comparison of the latter with the contact-altered slates (3·2 to 6·1) near the Mount Sorrel granite shows that there has been no noteworthy increase in the susceptibility of the altered rocks, and presumably, therefore, no appreciable development of magnetite as the result of the contact-alteration.

(b) *The Mesozoic Iron-Ores.*

(i.) *The Marlstone Iron-ores* occupy the actual surface or occur under at most a thin cover of Boulder Clay or Upper Lias Clay, the workings being abandoned wherever the thickness of cover exceeds 16 feet. As a consequence of the absence of cover the ores are almost completely oxidised, and are in the form of the hydrated ferric oxide limonite, while ferrous iron is wanting. Accordingly the susceptibility remains relatively low (10 to 23), even though the iron-content (reckoned as metallic iron) may attain to over 40 per cent.

(ii.) *The iron-ores in the Northampton Sands* round Waltham also occur for the most part under a comparatively thin cover, and again their oxidation is almost complete. Their susceptibility may be expected to compare closely with that of the exactly similar rocks which form the outcropping edge of the Northamptonshire Iron-ore in the Irthlingborough district (p. 89). The oxidised rocks of the outcrop consist essentially of limonite, and their susceptibility (6·0 to 8·3) is of the same order of magnitude as that of the Marlstone iron-ores mentioned above.

(c) *The Clay-Ironstones of the Coal Measures.*

These rocks consist of argillaceous material impregnated with ferrous carbonate. They occur as definite bands and as concretionary nodules interbedded with fire-clays, &c., at numerous horizons in the Coal Measures, and they are sufficiently rich in iron to have been worked near Dale in former years. It is well known that the presence of carbonaceous material exerts a retarding influence on the oxidation of ferous carbonate, and the iron in these clay-ironstones has remained in the ferrous condition in accordance with the general rule. The susceptibility is therefore considerably higher than that of the various limonite iron-ores of the Jurassic, and is

* Throughout this section the susceptibilities are given in units 10^{-5} of C.G.S. units.

comparable with that of the unoxidised carbonate ores from the Northampton Beds (see table below).

It is noteworthy that the susceptibilities of the iron-ores so far examined (pp. 85 and 86) appear to depend entirely on the chemical composition, and are not influenced by the texture of the deposits, and are to that extent independent of the geological horizon at which the ores occur. This is shown by the following figures :—

—			Susceptibility.	FeO.	Fe_2O_3.
				Per cent.	Per cent.
Limonite ores	N. 83.	Concretionary "Boxstone"	6	—	77·28
	N. 82.	Red oolitic ore, Northampton Beds, near Irthlingborough	8·31	—	44·76
	L. 71.	Red, fine-grained, vein-ore, Middle Lias, Leicestershire	10	—	53·12
	L. 63.	Red oolitic ore, Middle Lias, Leicestershire	21	trace	58·88
Carbonate ores	N. 89.	Green, sandy, oolitic ore, Northampton Beds, Irthlingborough	22	40·68	4·31
	N. 91.	Green oolitic ore, Northampton Beds, Irthlingborough	28	38·54	0·31
	N. 88.	Green-brown ore, Northampton Beds, Irthlingborough	29	36·96	12·00
	N. 90.	Green-silicate ore, Northampton Beds, Irthlingborough	36	49·32	0·80
	L. 19.	Clay-ironstone, Coal Measures	34·5	44·68	0·26
	L. 28.	" " "	21·5	34·28	2·32
		Chalybite (crystalline)	59	62·07 (theoretical)	—
		Ankerite, Coal Measures	10	not estimated	

(E.W. and A.H.C.)

2. The Igneous Rocks.

It has been found that different igneous rocks vary markedly as regards their volume susceptibility. This variation has no direct relation to the basic or acidic character of the rock. Acid rocks may have either high or low susceptibilities and similarly with basic rocks. The dominating factor that determines the susceptibility of an igneous rock is the amount of magnetite present in the rock, though there are doubtless other factors that play subordinate parts. Thus the presence of any mineral containing ferrous iron, *e.g.*, magnetic pyrites, ilmenite, hornblende, &c., will tend to increase the susceptibility, but the effects of such minerals are feeble compared with that of magnetite itself. The accessory iron-ores in igneous rocks occur mainly in one or more of three forms, namely: (i.) magnetite; (ii.) ilmenite; (iii.) intergrowths of ilmenite and magnetite. Accordingly in those rocks in which the accessory iron-ore is present as ilmenite, $FeTiO_3$, instead of magnetite, the susceptibility remains low even though the rock may be thoroughly basic with iron-ores occurring abundantly and in relatively large masses. On the other hand, a thoroughly acid rock in which iron-ores are relatively scarce, but consist entirely of magnetite, will have a high susceptibility. There is thus no direct connexion between the susceptibility and the basic or acid character of the rock.

The amount of magnetite present in any particular igneous rock is controlled not merely by the amount of iron in the original magma, but also by the physico-chemical laws that govern crystallisation from complex solutions. One factor that evidently exerts a considerable influence is the form of combination assumed by the TiO_2. In some rocks, the Mount Sorrel granite for example, part of the TiO_2 enters the biotite, the remainder combining with CaO to form sphene. In such a rock no TiO_2 is left free to combine with FeO to give ilmenite; consequently FeO is available to combine with Fe_2O_3 giving magnetite, and the rock will have a high susceptibility. In other rocks, some of the dolerites, for example, TiO_2 enters the augite, and again FeO is available to form magnetite. But in other examples—the granophyres and certain dolerites—either owing to TiO_2 not going to the augite, or to its being present in excess, a certain amount is left free to combine with FeO giving ilmenite. Consequently there is little or no FeO available to give magnetite, and the rock will have a low susceptibility. Adjustment between the two extremes depends upon a nice balance of conditions which may have varied within the limits of a single intrusion with consequent variations in the susceptibility values. The susceptibility of igneous rocks is, therefore, intimately connected with their petrography. Petrographical descriptions of the rocks tested are given in an addendum (p. 128).

There is the further possibility that different magnetites have different susceptibilities, a subject that is being further investigated by Prof. WILSON. The relative *size* of the crystals would not appear to enter into the question, judging from the results of Prof. WILSON's experiments on rock-powders (p. 87). Further experiments are in progress to ascertain whether the *distribution* of the magnetite exerts any controlling effect. The whole subject of the susceptibility of igneous rocks is in its infancy and much further work is needed. Meanwhile, the following notes on the rocks tested may be of interest.

(d) *Rocks of Low Susceptibility.*

As already stated, rocks in which the accessory iron-ore is mainly or entirely ilmenite have low susceptibilities irrespective of whether they are acid or basic. The same is true for any rocks that are considerably weathered, or by reason of their age or position have undergone changes analogous to weathering. Weathering results in the oxidation of any magnetite originally present, and consequently causes a rapid decrease in the susceptibility.

The various *rocks intrusive into the Charnian* are among those that have low susceptibilities, due to their accessory iron-ore being in the form of ilmenite or its alteration-product leucoxene. This is true of the *granophyres* whether of acid or basic types, and for the *porphyroids* or altered andesitic rocks, the figures of the three types being as follows :—

Acid granophyre or "syenite," Groby Quarry	4·0
Basic ,, "greenstone," Newhurst Wood	8·2
Porphyroid (or altered dacite), High Sharpley	1·3
	(E.W.)

The last-named rock has the lowest susceptibility of any of the igneous rocks tested.

Another rock with a relatively low susceptibility is the "*camptonite*" *from the Cambrian of Nuneaton*, the value found being 21. Accessory iron-ores were abundant in this rock, but they appeared to consist largely of ilmenite. The rock was, however, considerably weathered, and this may have further contributed in causing a low susceptibility.

The low value 12·5 for the *basalt lava* (toadstone) from the Carboniferous Limestone of Derbyshire is probably the result of weathering.

(e) *The Mount Sorrel Granite and Associated Rocks.*

The susceptibility values for the various rock types occurring in or associated with the Mount Sorrel mass vary considerably, as seen from the following figures :—

L. 15.	Normal granite—grey variety	65–130
L. 15A.	,, ,, ,, adjacent to "heathen" L. 015A	135
L. 16A.	,, ,, pink	45
L. 100.	Basic marginal granite	22
L. 015A.	Basic patch in grey granite ("heathen")	181
L. 016A.	,, ,, pink ,, ,,	40
L. 101.	Hornblende diorite	12
L. 103.	Basic dyke cutting granite	80
		(E.W.)

Thus the susceptibilities of the various basic rocks which are associated with the Mount Sorrel granite are not such that any magnetic effects due to the normal granite would be materially increased by the presence of the basic rocks. In fact, the basic marginal granite and the hornblende-diorite have actually lower susceptibilities than the typical granite.

In all these granitic rocks the accessory iron-ores are entirely in the form of magnetite, with the possible exception of the basic marginal granite in which some of the primary iron-ores may be sulphides. The presence of this magnetite readily accounts for the high susceptibilities of some of the rocks. But the amount of magnetite present is not a measure of the basicity of the rock. For example, one of the most basic rocks—the hornblende-diorite—contains the smallest amount of magnetite and accordingly gives the lowest susceptibility. Again, it is noticeable that magnetite is not necessarily present in increased amount in the basic patches, or "heathen," as compared with the normal granite, but tests on other specimens are needed before we are justified in analysing the results in detail.

(f) *Dolerites Intrusive into Coal Measures.*

The susceptibilities of the dolerites mentioned above (p. 101) are as follows:—

Ophitic analcite dolerite, Kelham	279	Figures by Prof. WILSON (p. 84).
,, ,, ,, Whitwick	391	
Basaltic dolerite, lower portion, Southwell	210	
Basalt, upper portion, Southwell	7	
Ophitic dolerite, centre portion, Owthorpe	9	
Basaltic dolerite, marginal portion, Owthorpe	434	
Basaltic dolerite, Rowley Regis	454	Figures by RÜCKER and WHITE.*
,, ,, Clee Hills	443	
Average of 45 dolerites and basalts from various parts of the British Isles	255	

Thus the olivine dolerites which occur in the Coal Measures have in general a high susceptibility, averaging about 400, but in some cases they exceed that figure. These high values are evidently due to the presence of magnetite in considerable amounts in the rocks. The lower figures sometimes given by apparently similar rocks are explained by the fact that in such rocks the iron-ore is in the form of ilmenite instead of magnetite.

In the dolerites and similar basic rocks the two minerals, magnetite and ilmenite, are frequently intergrown,† but the amount of each present in the intergrowth varies considerably. It is this fact that causes the wide differences observed in dolerites from different localities, and even in different specimens from the same mass, as in the Owthorpe example. RÜCKER and WHITE* determined the susceptibilities of four specimens from different parts of the Whin Sill (quartz-dolerite) as:—

263, 280, 345, 541,

whereas the petrologically similar rock at St. Davids had susceptibility 0.

* 'Roy. Soc. Proc.,' vol. LXIII. (1898), p. 466.

† J. J. H. TEALL, "On Chemical and Microscopical Characters of the Whin Sill," 'Q. J. G. S.,' vol. XL. (1884), p. 651, with references. E. B. BAILEY, "The Geology of the Glasgow District," 'Mem. Geol. Survey,' 1911, p. 128.

The intergrowth may show the external habit of magnetite or of ilmenite, and this may lead to apparent anomalies in the susceptibility results. Thus an estimation of the amount of iron-ore present, even in rocks in which the iron-ore *appears* to be all magnetite, does not necessarily yield a measure of the susceptibility, though it may be a guide in many, or even in the majority, of cases.

The susceptibility of weathered dolerites or basalts is low, as in all weathered rocks, even if the iron-ore content was originally high, as in the altered upper portion of the Southwell rock.

3. Summary.

The study of the magnetic susceptibilities of igneous rocks is in its infancy; the susceptibility is controlled by a number of factors the precise effects of which are at present unknown. It evidently depends mainly upon the amount of magnetite present, and is therefore independent of the acid or basic character of the rock.

The Mount Sorrel granite serves as an example of a rock with magnetite as the principal iron-ore, with resultant high susceptibility. The Charnwood (Groby) granophyre is similar to the granite as regards degree of acidity and minerals present, but its iron-ore is entirely in the form of ilmenite, hence the low susceptibility value.

In dolerites the minerals ilmenite and magnetite are frequently intergrown, sometimes the one, sometimes the other predominating. This may result in rapid variations of the susceptibility within the limits of a single intrusion. As a general rule, however, dolerites have high susceptibilities which are specially marked in dolerites of the type intrusive into Coal Measures.

III. Correlation of the Magnetic Results with the Composition and Tectonics of the Rocks.

Mr. Walker has produced evidence (Part I., p. 82) for the existence of "magnetic peaks" at three localities: (i.) Nottingham; (ii.) near Rempstone; (iii.) Melton Mowbray, with perhaps a fourth smaller "peak" near Pen Hill (see map, Plate Ap. 3).

The various rocks which in view of their iron content might conceivably cause magnetic disturbances, and which are known to occur in the district, are:—

(I.) The Northampton Iron-ores of the Inferior Oolite.
(II.) The Marlstone ,, ,, Middle Lias.
(III.) Dolerites intrusive into the Coal Measures.
(IV.) The Clay-ironstone of ,, ,,
(V.) Granites intrusive into pre-Carboniferous Rocks.
(VI.) Granophyres intrusive into Charnian Rocks.
(VII.) Andesitic intrusions and lavas in Charnian Rocks.

Other disturbing rocks might possibly lie concealed under newer Formations, though their presence within the district has not hitherto been proved. We must, therefore, consider also the probable magnetic effects of:—

(VIII.) Ferruginous dolomites in the Carboniferous Limestone.
(IX.) Hæmatite deposits ,, ,, ,,
(X.) Basalt lavas ,, ,, ,,
(XI.) Basic intrusions (Camptonites) in Cambrian Rocks.

It will only be necessary to consider (I.), (II.) and (III.) in any detail; (I.) and (II.) because the Jurassic iron-ores have a wide outcrop near the areas where the magnetic disturbances were observed, (III.) because of the high magnetic susceptibility of the dolerites. The others will be dealt with briefly in a later section.

1. *The Effect of the (Jurassic) Iron-ores.*

The limonite iron-ores of the Middle Lias Marlstone may at once be ruled out as incapable of originating the *main* disturbances.

In the first place their magnetic susceptibilities, which range from 10 to 20×10^{-5}, are not high enough, according to the susceptibility rule (p. 82), to cause disturbances measuring up to 170.

Secondly, the iron-ores occur as a nearly flat sheet capping a ridge of high ground that runs about four miles north of Melton Mowbray. The geological structure, as regards the Mesozoic (Triassic and Liassic) Formations, is almost symmetrical on the two sides of the ridge (see section, fig. 8, p. 121). But although the magnetic observation stations were more or less symmetrically disposed on either side of the ridge, the distribution of the disturbing forces on the two sides was found by Mr. Walker to be markedly unsymmetrical; the disturbances north of the ridge were comparatively small, whereas those south of it are very large.

Further, the sharpness of the changes as between the stations Melton Mowbray—Asfordby and Rempstone—Seagrave respectively, seem to bear no relation to the outcrop of the iron-ores, while the disturbances themselves seem to originate at levels much below the surface (see p. 82).

What has been said with regard to the Marlstone iron-ores applies with even greater force to the small development of iron-ore (Northampton Iron-ore) in the Inferior Oolite at Waltham, north-east of Melton Mowbray. The small patch there seen obviously cannot be the cause of the large disturbances measured at Rempstone, seven miles away to the west.

We must therefore look for some other agent if the cause of the asymmetry of the disturbances, and also their intensity, are to be explained. It will be seen in what follows that a study of the faulting of the rocks brings out a remarkable and suggestive correspondence between the tectonic and magnetic features of the region.

2. *The Coincidences between the Fault-Lines and the Magnetic Disturbances.*

The association of "magnetic-ridge lines"—that is lines or zones of considerable magnetic disturbance—with faults, has been noted by RÜCKER and THORPE* in the cases of the Great Glen Fault, the Southern Boundary Fault of the Highlands, and the Lilleshall—Church Stretton Fault.

In the district now being considered an examination of the distribution of the disturbing forces establishes a clear connexion between the magnetic disturbances and a system of east-west to south-east—north-west faulting. It can be shown that all the observation stations at which large magnetic disturbances, whether horizontal or vertical, were recorded, are situated on or in the immediate proximity to known fault-lines or their probable prolongations. In most cases these faults have only been proved in the Mesozoic rocks, but some of them are seen to affect both Mesozoic and Palæozoic formations.

Mr. WALKER has deduced (p. 82) "the presence of a pronounced line of disturbing matter running nearly east and west from Melton Mowbray to between Rempstone and Loughborough. Along this line the vertical disturbing forces attain their maxima at two points, one just south of Rempstone, the other a little west of Melton Mowbray."—G.W.W.

Near Rempstone a line of faulting has been definitely proved by the Officers of the Geological Survey.† Within one mile to the south of this village a pair of faults displaces the outcrops of the Mesozoic rocks—Keuper Marl, Rhætic, and Lower Lias—that of the Rhætic Beds being shifted as much as one and a-half miles. The faults are trough-faults throwing towards one another, the downthrow of the southern and larger fault being to the north, but the extent of the throw is not known. The strike of the faults is 20° S. of East to 20° N. of West, and they have been followed over a distance of five miles, so that they pass between Rempstone and Loughborough. (See map, Plate Ap. 3.) It is highly significant that the faulting crosses the intersection point of the arrows indicative of the direction of "relative" horizontal disturbance at Rempstone and Loughborough respectively.

East of Rempstone the line of faulting cannot be followed on the ground itself owing to the covering of Boulder Clay and to the absence of features among the soft Lower Lias Clays. But if prolonged, the line would pass near to Melton Mowbray.

In the Wreak Valley another fault—The Sileby Fault‡—has been proved to take an east-north-east course for over four miles. This fault, like the one at Rempstone, cuts Keuper Marl, Rhætic, and Lower Lias, and it also has a downthrow to the north. At the village of Hoby, six miles west of Melton Mowbray, it runs under the alluvium of the Wreak Valley, and cannot, therefore, be followed farther eastward; but, presumably, it continues under the alluvium, for it is noticeable that the Wreak

* 'Phil. Trans.,' Ser. A, vol. 188 (1896), p. 656, and Plate 14.

† 'Geol. Survey Map,' 1-inch (New Series), Sheet 142.

‡ "The Geology of the Country near Leicester," 'Mem. Geol. Survey,' 1903, p. 58.

Valley follows for several miles, between Hoby and Melton, a course which is coincident with the probable prolongation of the fault-line. Now the lines of the Rempstone and Sileby Faults would intersect at a point in the Wreak Valley just south-east of Asfordby Village, and about two miles west of Melton Mowbray. It is precisely at this assumed intersection-point of the two faults that the main magnetic disturbing centre is situated, as indicated by the intersection of the arrows showing the "relative" horizontal disturbing forces at Melton and Asfordby respectively (see p. 82).

That all four lines should intersect at one and the same point cannot be an accidental coincidence, especially when account is taken of the fact that the Loughborough and Rempstone disturbing forces also intersect on the fault-line.* It affords a strong presumption that the magnetic disturbances may originate in connexion with the fault, and that magnetic material is concentrated at particular localities along the fault-line.

So far then we have a fault-line running east-south-east between Rempstone and Melton Mowbray with disturbing centres near these two localities, resulting in large disturbances being measured at the stations Rempstone, Loughborough, Asfordby, Melton, and presumably accounting for the large disturbance at Waltham. The remaining stations at which large disturbances were observed, namely, Pen Hill and Nottingham, are also situated on other fault-lines.

A fault of small throw has been proved at Owthorpe to cut the Mesozoic Rocks.† This fault strikes 30° N. of West to 30° S. of East, that is, nearly parallel to the Rempstone Fault, the downthrow being again to the north-east. The fault if continued for three miles in the same direction would pass almost underneath the observation-station at Pen Hill. Five miles farther on along the same line, at White Lodge, a number of small step-faults are seen, all throwing to the north-east.

The "Nottingham" observation-station is situated half a mile east-north-east of Bramcote Church, and is on one of the most pronounced zones of faulting in the whole district. Faults pass on either side of the station at distances which cannot exceed a quarter of a mile,‡ while a third fault passes three-quarters of a mile to the south. These three faults are all parallel to one another, and they take an east-west course which defines the southern end of the exposed portion of the Nottinghamshire coalfield.

* The intersection-point at Rempstone, and possibly also the one at Asfordby, does not appear as mathematically exact so far as the plan, or map, is concerned. This is readily accounted for by the action of one or more of several factors, among the more obvious being that the fault-plane is presumably inclined to the vertical, and therefore, with increase in depth, its projection on to a horizontal plane suffers a lateral displacement. Further, the north pole of the disturbing mass need not necessarily be situate exactly on the line of the fault-plane. The latter factor invalidates any calculations as to depth of origin of the disturbances which might otherwise be made from the lateral displacement of the fault-projection.

† 'Geol. Survey Map,' 1-inch (New Series), Sheet 142.

‡ 'Geol. Survey Map,' 1-inch (New Series), Sheet 126.

Thus, in every case at which a marked magnetic disturbance was recorded, the station stands on or near a line of fault or its probable prolongation. Moreover, it is suggestive that of these stations the one recording the smallest disturbance, that is, Pen Hill, should stand on the fault of smallest throw.

3. The Probable Effect of Dolerite Intrusions.

Faults could only cause magnetic disturbances if (1) they dislocate rocks of high susceptibility, or (2) if rocks of high susceptibility have invaded the fault-planes.

It has been suggested by NAUMANN* that the connexion sometimes observed between lines of faulting and of magnetic disturbance depends not on rock-magnetism but on the effects produced on earth-currents by dislocations of the strata. This view was, however, opposed by RÜCKER and THORPE† on the grounds that the intensities and directions of flow of earth-currents as measured between various localities, including Melton Mowbray and Asfordby, were not such as could cause the observed magnetic disturbances. On the other hand, these authors showed that at other localities the susceptibility of certain igneous rocks was such that, assuming the rocks to be magnetised by the earth's induction, the magnetic disturbances would be explained.

The susceptibility determinations made by Prof. WILSON (p. 84) indicate that such olivine-dolerites as are known to occur in the Coal Measures of the concealed coalfield of Nottinghamshire have higher magnetic susceptibilities than any other rocks known in the district. It is, therefore, necessary to survey the evidence bearing upon the possible extension of such olivine-dolerites under the Melton Mowbray area, and their probable relations, if present, to the faulting and other tectonic features of the area.

(i.) A dolerite, intrusive into the Coal Measures, has been *proved by boring* to occur at −1750 feet O.D. *at Owthorpe*, three miles north-west of Pen Hill, which is a centre of minor disturbance. It is true that the thickness of dolerite passed through in the Owthorpe boring was only 40 feet, but the mass may well thicken laterally and so be the originator of the Pen Hill disturbance. It is noticeable that *at Pen Hill the "relative" horizontal disturbing forces are directed straight at Owthorpe with its dolerite intrusion.*

Similar dolerites have been proved again by deep bores (p. 98) to occur in the concealed Coal Measures at several localities, Southwell, Kelham, and Whitwick, all within 20 miles of Melton Mowbray. Also similar rocks are common as intrusions in the Coal Measures of other districts such as South Staffordshire, Shropshire, Northumberland, and Scotland, passing in places below the Coal Measures into the Millstone Grit, Carboniferous Limestone, or even with the Old Red Sandstone.

* 'Die Erscheinungen des Erdmagnetismus,' Stuttgart, 1887.

† 'Phil. Trans.,' Ser. A, vol. 181 (1890), p. 315.

(ii.) It has been shown to be highly probable that the Coal Measures extend under Melton Mowbray, seeing that they were proved to be 444 feet thick at Ruddington, six miles west of Owthorpe, and 800+ at Edwalton, nearer Owthorpe. Owthorpe itself is only ten miles north-north-east of Melton Mowbray, in which direction the Coal Measures strata are striking (p. 99).

(iii.) As regards Rempstone, the Coal Measures have not been proved nearer than Ruddington, five miles to the north, but it is known that the Carboniferous rocks approach nearer to the surface in a westward direction, as shown by their occurrence at 869 feet below O.D. at Owthorpe, 604 feet below O.D. at Edwalton, four miles west of Owthorpe, and at only 467 feet below O.D. at Ruddington, two miles further west.

Carboniferous rocks may therefore well be present at Rempstone, and at a less depth than at Owthorpe, in which case an intrusive mass at a similar horizon would exert an influence greater in proportion to its bulk.

(iv.) Basic rocks elsewhere usually show a high susceptibility. RÜCKER and WHITE* determined the mean susceptibility of 45 specimens of basalts and dolerites from various parts of the British Isles as 255×10^{-5}, and the mean of 12 from the northern counties as 340×10^{-5}.

As a consequence of their high susceptibilities, basaltic rocks give rise to considerable disturbances in those parts of the country where they are largely developed, as in Skye and Antrim. Further, RÜCKER and THORPE† have shown that there is a distinct magnetic pull towards the coalfields of the Central Valley of Scotland, and they have given good reason for supposing that the pull is due to the abundance of basic igneous rocks in the coalfields.

(v.) The susceptibility of olivine-dolerites found as intrusions in the Midland Coal Measures is, in general, higher than that usual in dolerites and basalts. The difference is brought out by the following figures :—

Olivine-dolerite (marginal basaltic), Owthorpe, Nottinghamshire	434×10^{-5}	Determination by Prof. E. WILSON (p. 84).
Olivine-dolerite (central), Owthorpe, Nottinghamshire	9×10^{-5}	
Olivine-dolerite, Whitwick, Leicestershire	391×10^{-5}	
,, ,, Kelham, Nottinghamshire	279×10^{-5}	
,, ,, (lower portion), Kirklington, Nottinghamshire	210×10^{-5}	
Olivine-basalt (upper portion) Kirklington, Nottinghamshire	7×10^{-5}	

* 'Roy. Soc. Proc.,' vol. lxiii. (1898), p. 466.

† 'Phil. Trans.,' Ser. A, vol. 188 (1896), pp. 621 and 653.

Olivine-dolerite, Rowley Regis, South Staffordshire	454×10^{-5}	Determination by RÜCKER and WHITE.*
Olivine-dolerite, Clee Hill, Salop	445×10^{-5}	
,, ,, (with nepheline), intrusive in Trias, Butterton, North Staffordshire	236×10^{-5}	
Average of 45 dolerites and basalts from various parts of the British Isles	255×10^{-5}	

Rocks of such high susceptibilities are certain to cause magnetic disturbances. Further, such rocks need not occur in exceptionally large quantity in order to cause disturbances such as those at Rempstone and Melton, measured by 170γ.

A difficulty arises from the fact that the central coarser portion of the Owthorpe dolerite shows the extremely low susceptibility 9×10^{-5}. This value is exceptionally low for a doleritic rock, but it may be purely local and due to the particular form taken by the iron-ores present in the rock (see p. 105). The figure will also be brought below the normal because of the extent to which the rock is impregnated with calcite. The figure should be compared with the higher values 391, 279, and 210×10^{-5} for the Whitwick, Kelham, and Southwell dolerites, and with 255×10^{-5} the average value determined for basaltic rocks by RÜCKER and WHITE.

(vi.) Intrusions being of quite local character, and often irregular in shape, are more likely to cause sharp changes in the character of the magnetic disturbances than sedimentary rocks occurring as horizontal or gently dipping sheets.

(vii.) Further, it is a well-known fact that in many areas the distribution of intrusions is intimately related to the faulting, and there is evidence that similar relationships hold in Nottinghamshire and Leicestershire, so that it is quite possible that the intrusions really represent fault-intrusions. In such case the sharp nature of the changes in the character of the disturbances between Rempstone and Loughborough, and again between Melton and Asfordby, might be readily explained. The point will be further elaborated below.

4. THE RELATIONSHIPS BETWEEN THE FAULTS, THE INTRUSIONS, AND THE MAGNETIC DISTURBANCES.

If it be granted that there is a strong probability that the origin of the magnetic disturbances is to be looked for in dolerites associated with the buried Coal Measures, it becomes necessary to enquire why they should only cause marked magnetic disturbances when they occur in the neighbourhood of faults. Intrusions may be related to faults in one of three ways :—

(*a*) The intrusions may be earlier than, and if so, may be displaced by, the faults.

(*b*) The intrusions may be fault-intrusions, that is, they may have arisen along the fault-planes during or after the progress of the earth-movements. From the fault-

* 'Roy. Soc. Proc.,' vol. lxiii. (1898), p. 466.

planes the intrusions are likely to spread out into the surrounding strata wherever there was a plane of weakness to give passage to the magma.

(*c*) There may be a combination of both the previous cases, due to earth-movements having been renewed at a later period along previously established lines of weakness. This last case represents the probable conditions in the Leicestershire and Nottinghamshire examples (see below, p. 117).

In any event it can be shown that the faults would increase the power of the intrusions to cause magnetic disturbances.

(*a*) RÜCKER and THORPE* have shown by experiments that a normal sill or dyke may cause but little magnetic disturbance at a distance, even if composed of a susceptible rock. This is because the two sides of the intrusion, when parallel and not too far apart, neutralise each other's effect at a comparatively short distance from the intrusive mass. For example, a dyke with parallel walls would give rise to a purely local vertical disturbance, but not to any appreciable horizontal disturbance. Thus intrusions might be present in non-faulted parts of the district without betraying their presence by any considerable magnetic disturbance. When, however, the intrusive mass is displaced by a fault, new faces are produced and a magnetic disturbance is liable to be set up. The amount of disturbance will depend not only on the susceptibility of the rock, but also on the hade of the fault and upon its throw.

(*b*) The second case, that in which the intrusions have arisen along the fault-planes and have spread thence into the surrounding strata, may next be considered. Intrusions of this type are generally found to be less regular in shape than normal sills and laccolites. The more irregular the mass the greater is the probability, *ceteribus paribus*, of its exciting magnetic disturbances. Now the olivine-dolerites in the English Coal Measures, although frequently sill-like in habit, are so commonly found in the immediate proximity of faults that there would appear to be more than a chance relationship between the two. For example, the proximity of the South Staffordshire dolerites to the faults in that coalfield has already been mentioned. The Whitwick dolerite (p. 101) apparently comes up along a line of north-west to south-east faulting which forms the eastern boundary of the Leicestershire coalfield.† Again, the occurrence of a north-west fault at Owthorpe, where a dolerite was proved by boring, has been described above (p. 112), while at Kelham a deep boring, almost certainly situated on an important line of faulting proved the presence of a dolerite which was pierced for 87 feet.‡

The close association of dolerites with faults is then so frequent that apparently in some cases the dolerites may act as fault-intrusions. As already stated, such intrusions are liable to be irregular, and hence to be potent causes of magnetic

* 'Phil. Trans.,' Ser. A, vol. 188 (1896), p. 639.

† "The Geology of the Leicestershire Coalfield," 'Mem. Geol. Survey,' 1907, p. 33.

‡ A. STRAHAN: Lecture to Royal Institution, "The Search for New Coalfields in England," March 17, 1916, p. 6.

disturbances, given such a high susceptibility for the rocks as exists in the examples mentioned.

Further, in the case of the Rempstone Fault, which has a downthrow to the north, "the distribution and magnitude of the disturbing forces does not agree with the hypothesis of a normal sill faulted down to the north. On the other hand, the distribution is such that it might well be given by a fault-intrusion along a fault hading to the north" (p. 111).—G. W. W.

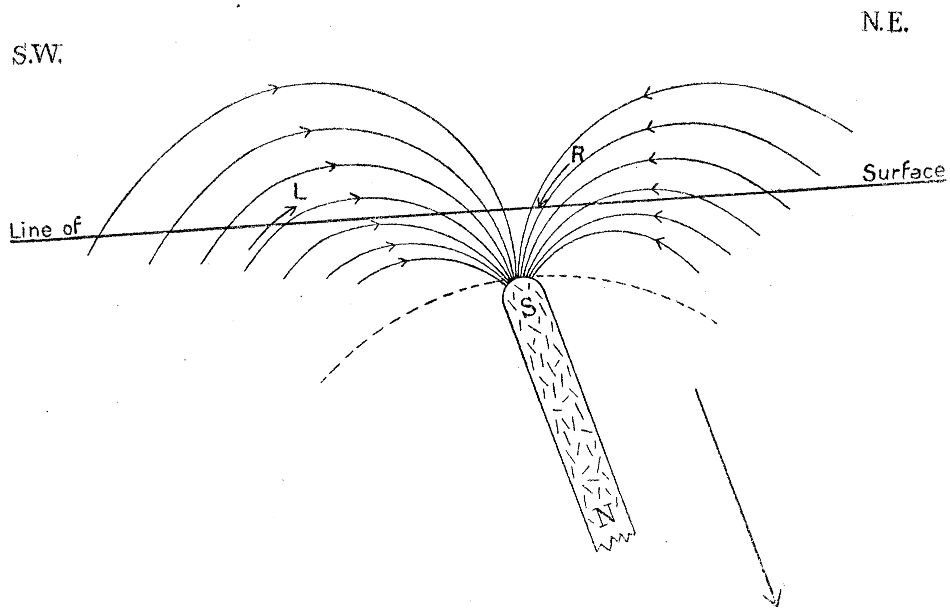


Fig. 7. Section to illustrate distribution of lines of force arising from an intrusion along a fault with a hade to the north as at Rempstone. L and R denote the positions of the observation stations at Loughborough and Rempstone.

(*c*) As regards the remaining possibility, that movement has been repeated along the faults at more than one period, there is strong evidence that this is actually the case. At Cinderhill, near Nottingham, there are faults, exposed both at the surface and in underground workings, which show clearly that movement has taken place along the same line at two different periods.* The principal movement was pre-Cambrian and the later movement post-Triassic in age, the displacement of the beds being much greater in the Carboniferous beds below than in the Permian beds above.

Now the Cinderhill Faults follow an east-west course parallel with, and only four miles north of, the Bramcote Faults, with which the "Nottingham" magnetic disturbance is to be correlated (p. 112). Further, it will be shown below (p. 122) that the whole of the structures among the Mesozoic rocks appear to be superimposed on structures developed in earlier times in the underlying Palæozoic rocks. Thus, if the dolerites are fault-intrusions, there is still the possibility that they may be

* Dr. Walcott Gibson, "The Concealed Coalfield of Yorkshire and Nottingham," 'Mem. Geol. Survey,' 1913, p. 39.

displaced by later movements along the faults. Such displacement might either increase or decrease the magnitude of the magnetic disturbances according to the relations between the shape of the intrusive mass and the throw of the fault.

To sum up, the evidence is all in favour of olivine-dolerites being the true disturbing agents, since such rocks are known to occur, to have a high susceptibility, and to be closely associated with faults.

Faulting is, however, but one of many expressions of the yielding of rocks under the stresses to which they have been subjected, and we may well seek further light from the other tectonic features of the district with a view to accounting for the local character of the intrusions.

5. The Structure of the Concealed Coalfield.

It will be noted that all the dolerites recorded from the Nottingham district have been discovered in deep borings into the concealed portion of the coalfield, whereas no single example is known to occur in the exposed coalfield, despite that in the nature of the case the exposed field is much better known than the concealed field. On this matter the structure of the coalfield has a decided bearing. The structure is explained by Dr. Walcott Gibson as due to the interaction of two movements of pre-Permian date. He writes: "By far the most powerful thrust came from the east. It was accompanied, or . . . . was preceded, by a secondary impulse from the south and south-east . . . . It is important to bear in mind that the impulse from the east was the most intense, and that to it is due the elongated north and south direction of the coalfield. At the southern end of the coalfield, east of Erewash Valley, it mastered the movement from the south, so that the east and west trend of the Coal Measures between Dale and Sandiacre is twisted round to the south-east, in which direction it is known that it extends past Ruddington . . . ." *

Structures ranging south-eastwards have been shown by Prof. Fearnsides† to play a prominent part further north in the coalfield between Mansfield and Sheffield. He has suggested that these structures were caused by the action of a pre-Permian thrust from the north-east which threw the Coal Measures into a series of folds arranged parallel with the north-west to south-east Charnian axis which lies to the south of the coalfield. He finds these south-east folds become more pronounced in the southern part of the coalfield, that is, in the part nearest to the main Charnian axis. As the south-east folds are followed towards the central trough-line of the coalfield, they curve round until they assume an approximately

* *Op. cit.*

† "Some Effects of Earth-movement on the Coal Measures of the Sheffield District.—Part II.," 'Trans. Inst. Min. Eng.,' vol. LI., part 3 (1916), p. 442 *et seq.*; see also Prof. Kendall in "Sub-report of the Concealed Portion of the Coalfield of Yorkshire, Derbyshire, and Nottinghamshire," Appendix III. to the Geol. Committee's Report in Part IX. of the 'Report of the Royal Commission on Coal Supplies, 1905,' pp. 18 *et seq.*

east-west direction. The change of direction is explained as due to a lagging of the southern ends of the folds as they approach the resistant barrier of Lower Palæozoic and older rocks which existed to the south.

Thus one may expect the southern end of the coalfield to have certain characteristics of its own as regards tectonic structure. Now it is highly significant that it is towards the southern end of the coalfield and where the bending of the strike of the beds into a south-east direction becomes most pronounced, and along the continuation of this south-east line and in the district east of it, that the east-west and south-east to north-west faults attain their greatest development, that the Owthorpe dolerites have been discovered, and that the magnetic disturbances at Rempstone, &c., have been observed. The inference is that the dolerites came up as a direct accompaniment or result of the south-easterly twisting, with concomitant south-east fracturing, of the Coal Measure strata. Hence the restricted distribution of the dolerites is explained. And hence, also, the magnetic disturbances in their turn may be ultimately connected with the change in the strike, while the change of strike suggests an approach to the southern limit of the basin of the coalfield.

If at this point of the concealed coalfield there are local occurrences of these highly susceptible intrusive rocks, an explanation could be given of an apparent anomaly in the course taken by one of the "magnetic ridge-lines" of RÜCKER and THORPE.*

This line swings from a north—south to a north-west—south-east direction along a course parallel, although not actually coincident, with the swing of the rocks. It runs first of all north—south approximately coincident with the Pennine Axis. But at a point north of Bakewell, Derbyshire, the line begins to swing off south-eastwards, crossing the strike of the coalfield obliquely to a point east of Nottingham, when it resumes its original north—south direction, and passes through Owthorpe and between Melton Mowbray and Rempstone. The course of this "ridge-line" may be attributed to the interaction of two quite different sets of disturbing agencies.

(i.) In the northern part of its course along the Pennine anticlinal axis, the disturbances are probably caused by more ancient rocks brought nearer to the surface by folding, so that the anticlinal region dominates magnetically the country on either side, where the older rocks are more deeply buried. The association of magnetic ridge-lines with anticlinal structures among the Palæozoic rocks was noted in several other districts by RÜCKER and THORPE.†

(ii.) The swing of the ridge-line away from the Pennine anticlinal axis, and its oblique traverse across the Coal Measure strata is apparently due to the incoming of the intrusive dolerites into the Coal Measures in the area between Southwell, Kelham, Owthorpe and Rempstone, that is, the area in which the south-eastern strike and the east-south-east faulting set in. The magnetic effects due to the high

* 'Phil. Trans.,' Ser. A, vol. 188 (1896), Plate 13.

† *Op. cit.*, p. 656.

susceptibility of these intrusions in the Coal Measures on the flank of the anticline gradually predominate over the effects of the older rocks which underly the anticline. Hence the "magnetic ridge-line" leaves the anticlinal axis and runs towards these highly susceptible rocks.

We have therefore obtained not only strong evidence that the local magnetic disturbances are due to local dolerite intrusions, but we have also seen that there are certain local features in the tectonics of the district, due ultimately to an approach to the southern limit of a syncline or basin, which might well account for the local occurrence of such intrusions.

The study of these local tectonic features, the real importance of which is emphasised by the magnetic disturbance, has led to certain conclusions relative to the deep-seated structures over a wide area.

6. The Presence of an Anticlinal Structure in the Mesozoic Rocks.

The south-easterly twisting of the Coal Measure strata was imparted, as already stated, as the result of a movement of pre-Permian age, and it applies to the strata of the concealed coalfield. The structure is not visible on the geological map, as the concealed coalfield is overlain by strata of the Permian, Triassic, and Jurassic Formations. These Formations sweep across country in a general north—south to north-north-east—south-south-west direction, in accordance with the usual trend of the Mesozoic strata, and apparently regardless of the structures among the older Formations below.

It will be recalled that the Cinderhill Faults (p. 117) showed that movements had been renewed in post-Triassic times along the lines of the earlier pre-Permian movement and that, as a result, the faults had a greater throw in the Coal Measure strata below than in the Permian and Triassic beds above. With this clear example before us, we may proceed to search for further indications of the Mesozoic rocks being affected by movements along lines initiated in Palæozoic times. Such indications are not far to seek.

The regularity of the north-north-east—south-south-west sweep of the Mesozoic rocks suffers a remarkable interruption within the district under consideration. This is best seen in the outcrops of the Rhætic and Lower Lias Formations. These follow a regular north—south course for 50 miles from the Humber in the north to a point south of Newark. Then they turn south-west for 15 miles as far as the Leak Hills, in the angle between the Trent and Soar Valleys. At the Leak Hills the outcrop swings round in a right-angled turn and strikes south-east for 10 miles as far as the Sileby Fault (p. 111), in the Wreak Valley. Immediately after crossing the fault the strike turns south-south-west and continues in this direction for about 50 miles to the southern parts of Warwickshire.

Between the Leak Hills and Sileby, the dip is to the north-east; while south of the Sileby Fault it is east-south-east. In other words, there is an anticlinal structure in the Mesozoic rocks, the centre of the anticline coinciding with the Wreak Valley.

These changes in the strike are also brought out by the courses of the main river-valleys. The Soar occupies a strike valley excavated in the soft Keuper Marls below the Rhætic escarpment, and it follows a south-east to north-westerly course from Syston in the Wreak Valley to its confluence with the Trent at Trent Junction. The Trent in its south-west to north-east course between Trent Junction and Newark is also a strike-stream, again flowing parallel with the Rhætic escarpment. The lines of the two strike-valleys, the Soar and the Trent, make a right-angle with one another, the angle signifying the point at which the strike of the Triassic beds suddenly changes owing to the strata coming within the influence of the northern limb of the anticline. At Syston, where the Soar is joined by the Wreak, the course of its valley suffers a change of direction, although the stream still remains a strike-stream. This second change is due to the strata having now crossed the anticlinal axis of the Wreak Valley and entered upon the southern limb of the fold.

Further information as to the northern limb of the anticline is obtained by combining the results gained from a consideration of the surface geology with those gained from a deep-well boring at Melton Mowbray. At Broughton Hill the base of the Middle Lias is about 420 feet above O.D.* Therefore, allowing a thickness of 670 feet for the Lower Lias† and of 35 feet for the Rhætic Beds,‡ the base of the

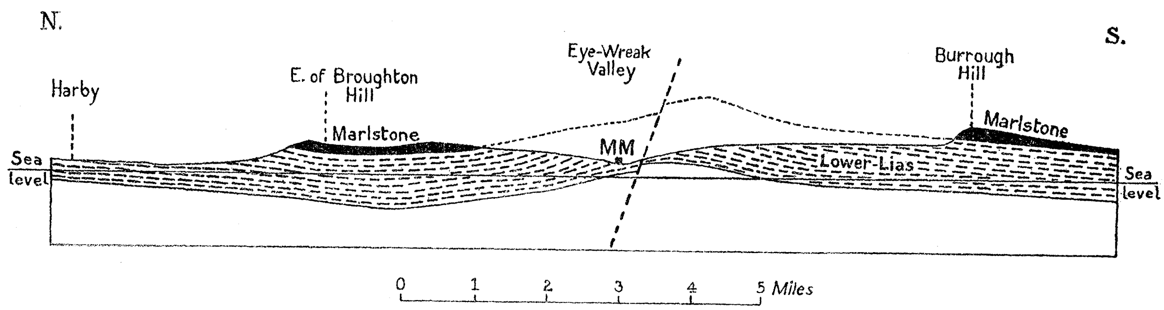


Fig. 8. Section to illustrate anticlinal structure in Jurassic Rocks at Melton Mowbray.

Rhætic would be at approximately 200 feet below O.D. But $3\frac{1}{2}$ miles to the south-south-east a deep-well boring on the northern side of Melton Mowbray showed that the base of the Rhætic was at only 15 feet below O.D.§ In other words, between Broughton Hill and the north side of Melton Mowbray the strata have risen 200 feet. This southward rise probably continues beneath the town of Melton Mowbray, and is probably increased by faults in the Wreak Valley, the

* 'Geological Survey Map,' 1-inch (New Series), Sheet 142.

† "The Geology of Melton Mowbray," 'Mem. Geol. Survey,' 1909, p. 22.

‡ *Op. cit.*, p. 104.

§ *Op. cit.*, p. 106.

continuations of the Rempstone and Sileby Faults (p. 111), so that the total uplift of the Mesozoic strata may be expected to amount to considerably more than 200 feet.

The outcrop of the Middle Lias follows a course parallel to that of the Rhætic, but the changes in strike in the district round Melton Mowbray are more pronounced in the case of the Middle Lias owing to the high relief of the ground caused by the harder character of the beds. The result is that the outcrop, after following the normal north—south or north-east—south-west course right from the Humber, is suddenly bent due east, and then sweeps round Melton Mowbray in a great crescent, six miles in diameter, before finally resuming the normal south-south-west strike, which is then maintained to the borders of Warwickshire and Oxfordshire. The centre of the Melton Mowbray crescent marks the anticlinal region.

In the country farther east, the outcrops of the succeeding rock-groups up to the Inferior Oolite are affected by anticlinal folding. In the various divisions of the rest of the Lower and of the Middle Jurassic, however, the outcrop gives no evidence of the presence of an anticline. The Upper Jurassic beds are hidden beneath the great spread of alluvium that borders The Wash, but in the outcrops of the Cretaceous rocks an anticline is again clearly visible. Throughout Lincolnshire, from the Humber to The Wash, the strike is south-east. But in Norfolk, south of The Wash, the strike is swinging round, and taking on the normal south-south-west direction. The Cretaceous rocks are therefore also affected by an anticlinal axis running north-eastward beneath The Wash. This may well be the continuation of the east—west anticlinal axis which we have traced from the Soar Valley past (south of) Melton Mowbray. It is evidently one of the most important structures in the Mesozoic rocks in this part of England.

7. Evidence for the Presence of an East—West Anticlinal Axis in the Concealed Palæozoic Rocks.

The principle that the lines of movement and the structures in newer rocks often follow ("posthumously") lines and structures existing in underlying rocks as the result of earlier movement is well known, and has been applied with success in many cases even though definite exceptions are known. If, now, we review the evidence that favours the application of this principle to the area now under consideration we obtain many clear indications that the post-Triassic movements followed the lines of earlier pre-Permian movements. There is firstly the evidence of the faults with a small throw in the Triassic rocks, and a much greater throw in the underlying Carboniferous rocks. Secondly, there is the fact that where the Palæozoic rocks in the concealed coalfield are twisted round to the south-east, the overlying Mesozoic rocks also suffer a local south-eastward twist, but to a lesser degree than in the case of the older rocks below. There is then a definite correspondence between the structures in the Mesozoic rocks and those in the Palæozoic rocks. The structures in the Mesozoic rocks are, as it were, a pale reflection of the more deeply situated structures. Since now the local south-eastern strike of the Mesozoic rocks has been shown to indicate the presence of an anticline with an approximately east—west axis, it is possible and even probable that this anticline, formed by post-Triassic movements, may be situated on the line of a stronger anticline initiated in the underlying Palæozoic rocks by pre-Permian movements.

In favour of the existence of such an old-established east—west anticlinal axis, there is other and independent evidence. In this connexion the isolated position of the pre-Cambrian rocks of Charnwood Forest has a considerable significance. Charnwood Forest is on the western continuation of the postulated east—west anticline and just where the anticline crosses the line of a more powerful north-west to south-east (Charnian) system of folding. Where the two lines of uplift cross there is the greatest elevation of the strata and the oldest rocks appear. Moreover, the southern part of the Charnwood anticline pitches to the south-east in the manner that would be expected if there were a cross-fold.* The later uplift, which resulted in the local denudation of the Triassic cover, may have been due in part to the newer folding which raised the Rhætic Beds 200 feet at Melton Mowbray (p. 122).

As regards the eastern continuation of the postulated anticline, it has been shown that the axis of the post-Cretaceous folding curves round eventually to the north-east, and passes through The Wash. It is probable that the axis of the older fold follows the same curving course, and it is suggestive that RÜCKER and THORPE† obtained evidence for the existence of a magnetic ridge line running north-east through The Wash, that is, along the line of such a hidden anticline.

The association of magnetic ridge-lines with axes of uplift among the older rocks is well established in other cases, as for example, the Pennine uplift mentioned above (p. 119). Conversely in one case the presence of a magnetic "ridge-line" has been used by Prof. KENDALL ‡ as lending support in favour of the existence of a buried anticline beneath the Mesozoic rocks of Lincolnshire.

In this connexion, however, it is important to bear in mind that "ridge-lines" are sometimes, perhaps often, the resultants of two or more independent sets of magnetic disturbances. In such case the resulting "ridge-line" need not conform to any definite geological line. The "ridge-line" previously mentioned (p. 119) as crossing the coalfield obliquely north of Nottingham is an example. Therefore, in the absence of geological evidence, one is not justified in correlating magnetic "ridge-lines" with

* W. W. WATTS, 'Geol. Mag.,' Dec., IV., vol. III. (1896), p. 485.

† 'Phil. Trans.,' Ser. A, vol. 188 (1896), plate 14.

‡ "Sub-report on the Concealed Portion of the Coalfields of Yorkshire, Derbyshire, and Nottinghamshire," 'Appendix III. to the Geol. Committee's Report in Part IX. of the Report of the Royal Commission on Coal Supplies,' 1905, pp. 20, 31, and 33.

anticlines. In the case of the Rempstone—Melton Mowbray disturbances, however, geological evidence is available, as detailed above.

Granted the presence of such an east—west anticlinal axis in the Palæozoic rocks beneath the Melton Mowbray area, the significance of the Rempstone—Melton Fault, which is otherwise lacking, becomes manifest. It would be a strike-fault running nearly parallel with the anticlinal axis, and on the northern flank of the fold. With its northerly downthrow it served to relieve the folding and to accentuate the anticlinal structure.

The line Rempstone—Melton Mowbray is thus one of considerable geological disturbance, as indicated by the post-Triassic folding and faulting, which appear to have been initiated on the lines of older structures among the Palæozoic rocks below. It is also a line of high magnetic disturbance, in other words, a "ridge-line," probably connected, as argued above, with occurrences of dolerite intrusions along the fault. It is within the limits of possibility that this line, along which the structure is anticlinal, marks a belt of folding and faulting that defines the at present unknown southern and south-eastern limits of the concealed coalfield. That the coalfield does not extend indefinitely to the south-east is shown by the presence of rocks older than the Coal Measures in various borings in East Anglia.*

Thus the magnetic survey has served to emphasise the real significance of a belt of faulting which, if judged only from its effects on the surface rocks, would appear to be of only minor importance.

The western continuation of the Rempstone Fault is lost under the great spread of alluvial deposits at the confluence of the Soar, Trent, and Derwent Valleys. But it is interesting to note that on the other side of the alluvium, a fault, again with a northerly downthrow, extends through the western outskirts of Derby, and thence in a north-north-westerly or north-westerly direction, bringing Lower Carboniferous Beds against the Trias.† This fault is in line with and may well represent the continuation of the Rempstone disturbance, in which case the curve of the Rempstone Fault from an east-west direction in the eastern part of its course to a north-west—south-east direction in the western part, would fall into parallelism with the curves of the anticlinal swells which cross the coalfield between Nottingham and Sheffield.‡

8. Other Possible Causes of the Magnetic Disturbances.

A number of other possibilities have been considered with regard to the origin of the magnetic disturbances. But in each case it can be shown that all the necessary conditions whereby the rock could give rise to the disturbances are not fulfilled.

* A. Strahan, "Pres. Address," 'Q. J. G. S.,' vol. LXIX. (1913), p. lxxxiv. and plate A.

† "The Geology of the South Derbyshire Coalfield," 'Mem. Geol. Survey,' 1908, p. 141; and 'Geol. Map,' New Series, 1-inch, Sheet 125.

‡ W. G. Fearnsides, "Some effects of Earth-movement on the Coal Measures of the Sheffield District . . . . . Part II.," 'Trans. Inst. Min. Eng.,' vol. LI., Part 3 (1916), p. 106.

The low susceptibility rules out such rocks as the *clay-ironstones* of the Coal Measures, also any *hæmatite deposits* or *ferruginous dolomites* or *basalt lavas*, such as might occur in the Carboniferous Limestone if present underground. Similarly, it would rule out the various intrusive rocks—*granophyres* and *porphyroids*—which occur in the Charnian, also the *camptonites* which might be present in any Cambrian rocks if such are developed in the district.

Effect of Possible Granite Intrusions.—Apart from the dolerites, the only rocks of a susceptibility approaching that demanded by the magnitude of the disturbances, are the *Mount Sorrel granite* and associated rocks. The value ranged from 60 to 130×10^{-5} for the typical rock to as high as 181×10^{-5} for the included basic patches or "heathen," which are often very abundant. The latter figure is comparable to that given by dolerites, and the question arises whether the disturbances noted can be ascribed to the buried masses of granite rather than to dolerites.

Unfortunately, there is no observation station within four miles of the visible granites, so that we do not know whether the Mount Sorrel mass itself exerts any disturbing influence. It is suggestive, however, that the large disturbance at Loughborough, the station nearest the granite, shows no connexion with the visible granite four miles south-east, but associates itself with the Rempstone centre of disturbance, that is, the Rempstone Fault, four miles north-east of Loughborough. This would seem to tell against the granite exerting any great influence, unless, indeed, there should be a larger or more powerful granite mass under Rempstone.

Again, there is an almost complete lack of geological evidence either for or against such an hypothesis. The Mount Sorrel granite is, so far as surface exposures go, an isolated mass. But it has been shown (p. 102) that in view of its petrological character, and probable age, no similar granite could be expected to occur in Carboniferous or newer rocks, although similar granites might well occur in rocks older than the Carboniferous. Thus the Mount Sorrel intrusion may not in reality be as isolated as it appears, and there may be other granites in the district that could give rise to disturbances.

The Charnian rocks, with which the granite is associated, continue underground under a comparatively shallow cover along their direction of strike, that is, to the south-east. But to the north-east the irregular plane of junction between them and the overlying Trias usually dips steeply. Therefore any Charnian rocks would most likely lie very deep under Rempstone, four miles north-east of the outmost Charnian strike-line, and possibly still deeper under Melton Mowbray, 10 miles from the line. On the other hand, Carboniferous rocks, with possibly associated dolerites, almost certainly intervene at lesser depths, as previously described.

Dr. WALKER writes: "Since the granites may attain a susceptibility of nearly 200×10^{-5}, they become a possible source for disturbances measured by 200γ, as at Rempstone. Their susceptibility, however, according to the rule (p. 82), represents about the minimum value necessary to cause disturbances of the magnitude observed. Hence the granites would require to *come very close* to the surface, and to fill up a *large part of the area* between Rempstone and Loughborough, and again between Melton, Asfordby and Waltham. The known geology is, I gather, against this. Dr. Cox informs me that it is most unlikely that any granite could come within 1000 feet of the surface at Melton Mowbray, or even within 3000 feet of the surface if, as seems probable, the Coal Measures occur under the cover of the newer rocks. Thus we appear to be forced to an explanation by rocks of still higher susceptibility, such as the dolerites, involving logically a greater depth or a smaller bulk of such rocks."—G.W.W.

With regard to the influence elsewhere of granites and similar rocks, RÜCKER and THORPE* state that: "In general, masses of non-basaltic rock, igneous rock, produce little or no effect on the needle" . . . . but they note exceptions to this rule in the case of the granites of the Cheviots and of Galway.

PART IV.—SUMMARY AND CONCLUSIONS.

After considering the geology of certain areas in which anomalous magnetic disturbance had been brought to the notice of the Conjoint Board of Scientific Societies, as stated on p. 75, the Iron-ore Committee of the Board formed the conclusion "that it is not possible at present to see any connexion between the observed magnetic disturbances and known occurrences of iron-ore in this country." The committee resolved that "the causes of the disturbances are deserving of further investigation and they recommend that attention should be concentrated upon two dissimilar areas, such as the neighbourhood of Melton Mowbray and that of Strachur and Lochgoilhead, that a detailed geological and petrographical survey of the rocks in each region investigated should be carried out, and that the magnetic permeability of these rocks should also be investigated."

In pursuance of this recommendation the magnetic and geological surveys were carried out in the summer and autumn of 1917, and the materials collected subsequently submitted to magnetic, chemical, and petrographical examination.

The district chosen was that of Melton Mowbray, where the nearest superficial iron-ores are four miles distant from the point at which the magnetic disturbances were originally observed, and as a control, a parallel examination was made in an area of undisturbed Northampton iron-ore near Irthlingborough, the boundaries of which have been surveyed and are accurately known.

The weak magnetic disturbances of the Irthlingborough district can be correlated with the distribution of the Jurassic iron-ores, which are in the form of a horizontal sheet of weakly susceptible ferrous carbonate when protected from weathering by overlying impervious strata, passing into less susceptible hydrated ferric oxide at the weathered outcrop.

* 'Phil. Trans.,' Ser. A, vol. 188 (1896), p. 653.

The disturbances arising from material only feebly magnetic are quite capable of detection and may be of use in determining the boundaries of the sheets in areas not affected by larger disturbances of deep-seated origin.

In the Melton district the disturbances cannot be correlated with Jurassic iron-ores, which have been removed by denudation from all but a margin of the area, or with the Coal Measure clay-ironstones (weakly susceptible) which may possibly occur in depth.

On the other hand the magnetic disturbances, which are inferred from their distribution to originate at a considerable depth, exhibit a remarkable correspondence with certain easterly to westerly faults which cut the Mesozoic rocks, and in some cases are also seen to cut the Palæozoic rocks to the west of the area. It is practically certain that all these faults must extend downwards into the deeper seated rocks, which may be of Coal Measure age or older.

As none of the sedimentary rocks known in the district have susceptibilities high enough to account for magnetic disturbances of the magnitude observed, attention was given to the igneous rocks which are known to occur in parts of the district and might possibly underly the areas of disturbance.

Measurement of the susceptibility of a number of igneous rocks shows that this property is largely independent of the acidity or basicity of the rock but is chiefly related to the amount of magnetite present, even if in a widely scattered form. Of the rocks examined, all except certain dolerites have susceptibilities not high enough to account for the magnitude of the disturbances when allowance is made for the depths at which they are likely, if present, to occur.

Dolerites intrusive into the Coal Measures, however, prove to possess the highest susceptibilities of any rocks found in the district, sufficiently high to produce the results observed if occurring at depths about equal to the probable thickness of the Mesozoic and Permian rocks there. Basic rocks elsewhere are known to give rise to magnetic disturbances in several districts where they are largely developed, as in Skye and Antrim, and RÜCKER and THORPE have suggested that the magnetic pull towards the coalfield of the Midland Valley of Scotland is due to the abundance of basic rocks there.

Such rocks, though absent from the exposed coalfield, have been found in several borings and shafts in the concealed coalfield, and probably may be associated, directly or through faulting, with the easterly bending of the north—south strike of the rocks of the coalfield. They may be a feature of the southern rim of the coal basin.

A consideration of the evidence renders it likely that the intrusions have been injected into faults, though the latter may possibly have undergone secondary movement at a later date.

The outcrop of the Mesozoic rocks gives evidence of an anticlinal axis parallel with the Rempstone—Melton Fault, which may well be founded on an anticline in the deep-seated Palæozoic rocks, the higher beds of which, if the above explanation of the magnetic disturbances be correct, will include Coal Measures. Thus the fault may be an anticlinal fault, and the anticline may be the southern termination of the concealed coalfield.

Although this investigation has shed some light on the structure of a concealed coalfield, it will be obvious that magnetic disturbances cannot be taken, without other geological evidence, as proof of the existence of a concealed coalfield; nor, on the other hand, is a coalfield necessarily accompanied by magnetic disturbance.

It is clear, however, that the investigation of magnetic disturbances is a promising method of probing into the difficulties of underground structure. The elucidation of underground structure is not only one of the most fascinating branches of geological research, but it is at present one of the most pressing lines of enquiry from an economic as well as a scientific point of view. The necessity of such knowledge is brought home every day in the problems connected with the structure of the coal-fields, whether they crop out at the surface or are concealed by a cover of newer rocks. Our chief sources of information are based on geological mapping supplemented by such deep borings as have been made. The results obtained from the present joint magnetic and geological research show that there may be other methods of attacking the problem, and that an extension of these methods to other parts of the country is likely to yield information of considerable national importance.

ADDENDUM.

Petrology of the Igneous Rocks.

1. *The Dolerites.*

Petrologically the Nottinghamshire and Leicestershire dolerites have many features in common which suggest that all the intrusions belong to one and the same period. They are ophitic to sub-ophitic or granular olivine-dolerites carrying a purplish pleochroic augite and a certain amount of analcite. They show affinities, therefore, to the teschenites, using the term in its wider sense. If redescribed they would probably be compared with the crinanites or analcite-olivine-dolerites of Argyleshire* so far as petrological characters are concerned, though not necessarily so as regards age.

The Whitwick dolerite has been described by Sir J. J. H. Teall† and by Dr. J. S. Flett, who remarks:—"The rock (E. 890) is a fresh and very characteristic ophitic olivine dolerite. The olivine is in numerous rounded grains which are passing into serpentine along their edges and in their centres. The augite of purplish-brown colour forms large ophitic plates, enclosing many lath-shaped plagioclase felspar.

* J. S. Flett, "The Geology of Knapdale, Jura . . . . ," 'Mem. Geol. Survey,' 1911, p. 117.

† 'Brit. Petrog.,' 1888, p. 211.

Iron-oxides and apatite are abundant, and considerable areas of the slide are occupied by granular turbid semi-opaque analcite."*

The susceptibility for the typical Whitwick rock is 391×10^{-5} as compared with the values for the marginal and central portions of the Owthorpe dolerite 434 and 9×10^{-5} respectively. The differences in the figures are evidently accounted for by differences in the amounts and composition of the iron-ores in the three rocks. These differences are well brought out in the description of the Owthorpe dolerite by Dr. H. H. THOMAS as follows :—

"In the hand specimen the typical rock (E. 6520) taken from well inside the mass, at a depth of 1966 feet from the surface is grey in colour and moderately coarse in grain ; crystals of augite and felspar are visible to the unaided eye. Towards its upper surface the mass becomes much darker, finer in grain, and more compact (E. 6518–19). A specimen taken from about nine feet below the upper limit at 1953 feet from the surface is almost black in colour and evidently rich in iron-ores.

"Under the microscope the coarser rock (E. 6520) proves to be an ophitic olivine dolerite, composed of augite, olivine, plagioclase-felspars, and accessory iron-ores.

"The augite which is evidently a highly-titaniferous variety has a rich plum-colour, is pleochroic, and forms ophitic plates, enclosing and being penetrated by the felspar laths.

"Olivine replaced by calcite pseudomorphs occurs somewhat sparingly in granules, but a few idiomorphic crystals were noticed.

"The felspars apparently are all basic plagioclase approximating labradorite ; they are zoned, and occur chiefly as much twinned narrow laths. *The iron-ores were originally almost all ilmenite,* but are now converted into leucoxene pseudomorphs.

"There is very little base, and practically no apatite. A few cavities have been filled with radiating masses of calcite having a nucleus of silica.

"The *finer-grained rock* (E. 6518–19) presents properties which would without any other evidence lead us to regard it as occurring nearer to the margin of the mass. The minerals are the same as those in the coarse variety described above, but there are certain differences which have a bearing on the origin of the rock. It *contains a large amount of glassy base rendered almost opaque by rods and skeleton-crystals of iron-ores.* Olivine is more plentiful, and there is an increased prevalence of crystals with good outline. The augite occurs in smaller plates, and there is a marked tendency towards idiomorphism.

"Small chlorite-lined cavities contain colourless isotropic analcite, while a good deal of chlorite and serpentinous material has been localised in the decomposing felspar.

"From the above characters, especially the *apparent segregation of the olivine and iron-ores* towards the margin of the mass, it would seem that the rock is intrusive in character.

* "Geology of the Leicestershire Coalfield," 'Mem. Geol. Survey,' 1907, p. 35.

"Compared with the rock met with in the shaft of the Whitwick Colliery, the Owthorpe dolerite presents a general similarity; there are, however, several features in which it differs. It has a smaller proportion of olivine, and this mineral at Whitwick is altered to serpentine instead of being replaced by calcite. The Owthorpe rock has a deeper coloured augite, less apatite, more iron-ores and *more ilmenite than magnetite*."*

The rock from the Southwell boring (p. 101) also shows a considerable variation in different parts of the mass. A specimen from the lower portion (L. 113) is a granular non-porphyritic olivine dolerite or basalt. Olivine is abundant in large sharply idiomorphic crystals now mainly replaced by serpentine; it includes scattered granular and idiomorphic iron-ores. Augite is likewise abundant in small crystals, some idiomorphic, others with only the prism faces developed, and others quite irregular in shape. It is pale green in colour and there is no marked dispersion of the opti axes. Plagioclase gives the usual lath-shaped sections with no sign of flow-structure. It is strongly zonal, the average composition being that of an acid labradorite between Ab_1An_1 and Ab_2An_3. It is remarkably fresh and shows in this specimen no sign of analcitisation. There is also a green pleochroic chloritic material with fairly high birefringence occurring in radiating fibrous masses of later formation than the felspars. Where only present in small patches, and also along the borders of the larger areas, the substance is rendered almost opaque by iron-ore microlites, but the centres of larger areas are remarkably free from iron-ores. The substance is probably analogous to delessite and represents an altered glass. Calcite is also of local occurrence as an interstitial material, or as replacements of original minerals.

The iron-ores occur mainly as long rods with ragged edges cutting the other minerals. Occasionally the rods swell out into larger masses which have variable relations to the other minerals, sometimes being posterior to felspar and to augite. There is evidently a larger relative amount of the ilmenite molecule present in the Southwell rock as compared with the Whitwick rock (p. 128). The iron-ores comprise about 6 per cent. of the rock, the susceptibility being 210×10^{-5}.

Other slides (E. 11,442–11,444) taken from nearer the top of the mass show rocks of different aspect. The rock is now considerably altered, hand specimens having a light green colour instead of the usual dark basaltic appearance. The rock is a vesicular fine-grained olivine-basalt, consisting of decomposed basic plagioclase felspars, often with skeletal terminations, set in a once glassy base which is full of skeletal growths of felspar, and rendered almost opaque by finely divided iron-ore. The olivine has completely altered to serpentine, and any augite that may be present has also been completely altered. The percentage of iron-ore cannot be estimated under the microscope on account of the fine-grained character of the rock. The susceptibility is 7×10^{-5}, the low value probably being due to the altered condition of the rock.

* "The Geology of Newark and Nottingham," 'Mem. Geol. Survey,' 1908, p. 19.

The rock from Kelham boring (p. 101) is in some respects more similar to the Whitwick rock. It is an ophitic to subophitic teschenite containing augite and serpentinous pseudomorphs after olivine. It is rich in analcite and the felspars are partly analcitised. It differs from the Whitwick rock in being somewhat fine-grained, and in containing an abundance of some dark-brown interstitial material which is probably a glass free from crystallites of iron-ore.*

Iron-ore constitutes about 4 per cent. of the rock, and is partly in the form of rods and partly as square, rectangular, or rather irregular grains up to 0·1 mm. in diameter. It is evidently proportionally richer in magnetite than the typical Southwell specimen. The susceptibility was 279×10^{-5} after demagnetisation.

2. *The Mount Sorrel Granite and Associated Rocks.*

There are two main varieties of the granite—a grey and a pink variety. In the Mount Sorrel quarries these two varieties occur intricately intermingled one with the other, but apart from the colour, there does not appear to be any marked difference.

With the normal granite there are associated various types of more basic rocks. These include (i.) the basic marginal granite, (ii.) the basic patches or "heathen," (iii.) the diorite of Brazil Wood, and (iv.) basic dykes.

The grey variety is a typical coarse-grained, non-porphyritic granite composed of plagioclase and orthoclase felspars, hornblende, biotite, quartz, and accessory minerals, the latter including magnetite and sphene.

The plagioclase is present in somewhat greater amount than the orthoclase and it builds larger crystals, which are often well formed and are strongly zonal, the composition of the central portions being that of a medium andesine varying to an acid oligoclase in the outer portions. The mineral is generally rather fresh, but it may show the usual alteration which is sometimes guided by the zoning. The orthoclase, especially in larger crystals, shows a patchy extinction owing to perthitic structure. The relations between orthoclase and quartz are variable, sometimes the one, sometimes the other showing the better crystal form, but only occasionally are there any indications of graphic structure. The hornblende is pale green in colour and builds ragged crystals which occasionally enter into a sort of graphic intergrowth with quartz. It is usually subordinate in amount to the biotite, which latter mineral shows the characters usual in granites. Calcite occurs in small amounts as an interstitial constituent or replacing hornblende. Sphene occurs as large wedge-shaped crystals and as irregular granules, many of the latter being included in biotite. Pyrites is present locally as irregular masses in felspar spreading in dendritic fashion partly guided by the felspar cleavage. Magnetite occurs as grains enclosed in any

* J. S. FLETT in "The Concealed Coalfield of Yorkshire and Nottinghamshire," 'Mem. Geol. Survey,' 1913, p. 58.

of the other minerals, but rather irregularly distributed. It constitutes a little under 1 per cent. of the rock.

The pink variety of the granite shows no essential difference as far as the microscopical characters are concerned, but its susceptibility appears to be lower than that of the grey granite.

The granite differs from the dolerites described above and from the granophyres described below (p. 134) in the way in which its TiO_2 is combined. In the dolerites and in the granophyres a large part of the TiO_2 has combined with FeO to form ilmenite, while in the dolerites a part of the TiO_2 may also be present in the augite molecule. But in the granites part of the TiO_2 entered the biotite, from which, as the result of secondary changes, it has since separated as rutile. The remainder of the TiO_2 entered into combination with CaO to form sphene, although the CaO percentage in the granite is less than that in the dolerites. The result is that ilmenite is absent from the granite.

The basic granite of Brazil Wood is a marginal facies of the main mass of the Mount Sorrel intrusion. In the hand specimen it is finer grained and much darker than the normal granite, resembling rather a dolerite at first sight. Occasional pink felspars approach in size the felspars of the normal pink granite, giving a pseudo-porphyritic character to the rock. Under the microscope the constituents are seen to be the same as in the normal granite, but plagioclase and the dark minerals, especially hornblende, are present in greatly increased amount and are more idiomorphic than in the parent rock, while orthoclase and quartz are in decreased amount, being reduced to interstitial constituents, the quartz sometimes acting pœcilitically as host to all the other minerals. The plagioclase is zonal and is slightly more basic than that in the normal granite, having the composition of an andesine-labradorite, approximately Ab_1An_1. TiO_2 is again combined with CaO to form sphene.

Original iron-ores occur (1) as distinct granules of magnetite as in the normal granite, and (2) as a fine dust irregularly distributed in the other minerals, and abundant in certain areas, but absent from some of the larger felspar crystals. This dust may consist in large part of sulphides, not of magnetite. Pyrites also occur aggregated in patches as in the normal granite and is probably formed by secondary changes. On account of the fine state of division of much of the iron-ore it is not possible to get a satisfactory estimation of the amount of magnetite present. The susceptibility is considerably lower than that of the typical grey or pink granite.

Basic patches or "heathen" are abundant in both types of the normal granite. They are of all shapes and sizes, and in the hand specimen the junctions with the normal rock appear to be quite sharp. They are darker in colour and much finer grained than the surrounding matrix of normal granite.

Under the microscope the texture is seen to be quite different from that of the basic marginal granite described above. The "heathen" consist mainly of a felted mass of plagioclase and orthoclase felspars. Quartz is, as a rule, only present as an interstitial constituent of minor importance, but occasionally it takes on a pœcilitic habit as in the basic granite. Dark minerals were abundant and were originally represented by hornblende which was quite allotriomorphic, not idiomorphic as in the basic granite. The hornblende is now entirely replaced by chlorite in the specimens examined. In fact the minerals in the "heathen" always present the appearance of being more "weathered" than the corresponding minerals in the matrix. The plagioclase is, curiously enough, represented by albite or albite-oligoclase clouded by secondary products and possibly itself being of secondary origin. Along the junction with the normal granite large orthoclase crystals may extend from the matrix into the "heathen," and then become packed with small inclusions of plagioclase and of ragged chlorite after hornblende. One half of such an orthoclase may belong to the coarse matrix and be free from inclusions, while the other half is in the "heathen" and is full of inclusions.

Iron-ores are mainly represented by magnetite which has a habit similar to that in the normal granite, except that the magnetites in the heathen are smaller and sometimes, but not invariably so, more abundant than those in the granite. The amount of magnetite varies between 0·5 and 1·5 per cent., and the susceptibilities are sometimes higher, sometimes equal to those of the surrounding matrix.

The *hornblende diorite* of Brazil Wood occurs close to the Mount Sorrel granite, but its relations to the granite have never been exposed to view.* It is a coarse-grained, almost basic, rock (E. 2063) of simple mineralogical composition, consisting almost entirely of bytownite felspar and hornblende. The hornblende is of posterior formation to the plagioclase, and is partly converted into actinolite. Despite the almost gabbroid character of the rock magnetite only occurs in small quantity and, as a rule, only in minute grains, though there are occasional larger and more irregular masses embedded in the hornblende. The total amount of magnetite is, however, much smaller than in the granites. Hence, presumably, the low susceptibility (12×10^{-5}) of the rock.

Basic dykes in the Mount Sorrel granite. The granite is cut by a number of basic dykes. An example from one of the freshest of these rocks seems to have been an ophitic dolerite, but it is considerably decomposed, the augite being largely replaced by chlorite, calcite, and quartz, while the plagioclase is filled with micaceous products along with chlorite, secondary sphene, and epidote. Iron-ores are abundant in large crystals giving square or irregular cross-sections, and also as skeletal rod-like growths. They appear to be entirely magnetite and constitute rather more than 3 per cent. of the rock, the susceptibility being 80×10^{-5}, which is approximately equal to that of the grey granite.

* W. W. WATTS, "Charnwood Forest," 'Geology in the Field,' vol. II., 1910, p. 777.

3. *Camptonites Intrusive into Cambrian.*

The petrology of these rocks has been described by Sir JETHRO TEALL* and by Prof. WATTS.†

The specimen tested is a medium to fine-grained rock originally of ophitic texture. The dominant felspars consist of cloudy albite giving small lath-shaped sections more or less idiomorphic. Some orthoclase is also present. The rock is much decomposed, and the original dark minerals, which must have been abundant, are entirely replaced by chlorite and calcite. A small amount of quartz is present, but is probably of secondary origin. Sphene is abundant in small granules scattered through the other minerals. It also is probably of secondary origin. Iron-ores are abundant in highly irregular granules, which probably consist in large part of ilmenite, and the susceptibility is low—21×10^{-5}. The rocks were originally known as diorites, but Prof. WATTS showed that from their characters they should be grouped with the lamprophyres. The example described above appears very similar to certain lamprophyric rocks known as cuselites.

4. *The Igneous Rocks of Charnwood Forest.*

(*a*) *The Granophyres* have been described on various occasions by Sir JETHRO TEALL,‡ and by Prof. BONNEY and Mr. HILL,§ so that a brief reference will suffice.

Two main types are recognised—an acid and a basic type. The rocks are rather coarse-grained comparable with granite, and are now considerably decomposed. They consist of idiomorphic plagioclase and augite, which has been altered to chlorite, epidote, and actinolite, set in an abundant granophyric ground-mass of quartz and orthoclase. The character and grain of the intergrowth varies considerably. The iron-ore builds rather large masses scattered irregularly through the ground mass. They show partial alteration to leucoxene and evidently consisted originally of ilmenite, not magnetite. Hence the low susceptibility of the rock as compared with the Mount Sorrel granite.

The more basic type, found in the northern part of the Forest, is similar in general characters, differing mainly in the degree of acidity and in the relative proportions of the various minerals and in being still more decomposed. The quartz and orthoclase are reduced in amount and the graphic intergrowth is finer grained. Plagioclase and the dark minerals are present to a greater extent but are completely altered with the resulting development of a large amount of chlorite and epidote. The rocks present certain affinities to the quartz dolerites, and apparently represent a transitional type

* 'British Petrography,' 1888, p. 250.

† 'Proc. Geol. Assoc.,' vol. XV. (1898), p. 394.

‡ 'British Petrography,' 1888, p. 270.

§ 'Q. J. G. S.,' vol. XXXIV. (1878), p. 217; and vol. XLVII. (1891), p. 84.

between normal granophyres and quartz dolerites. The iron-ore is all in the form of leucoxene and the susceptibility is again low.

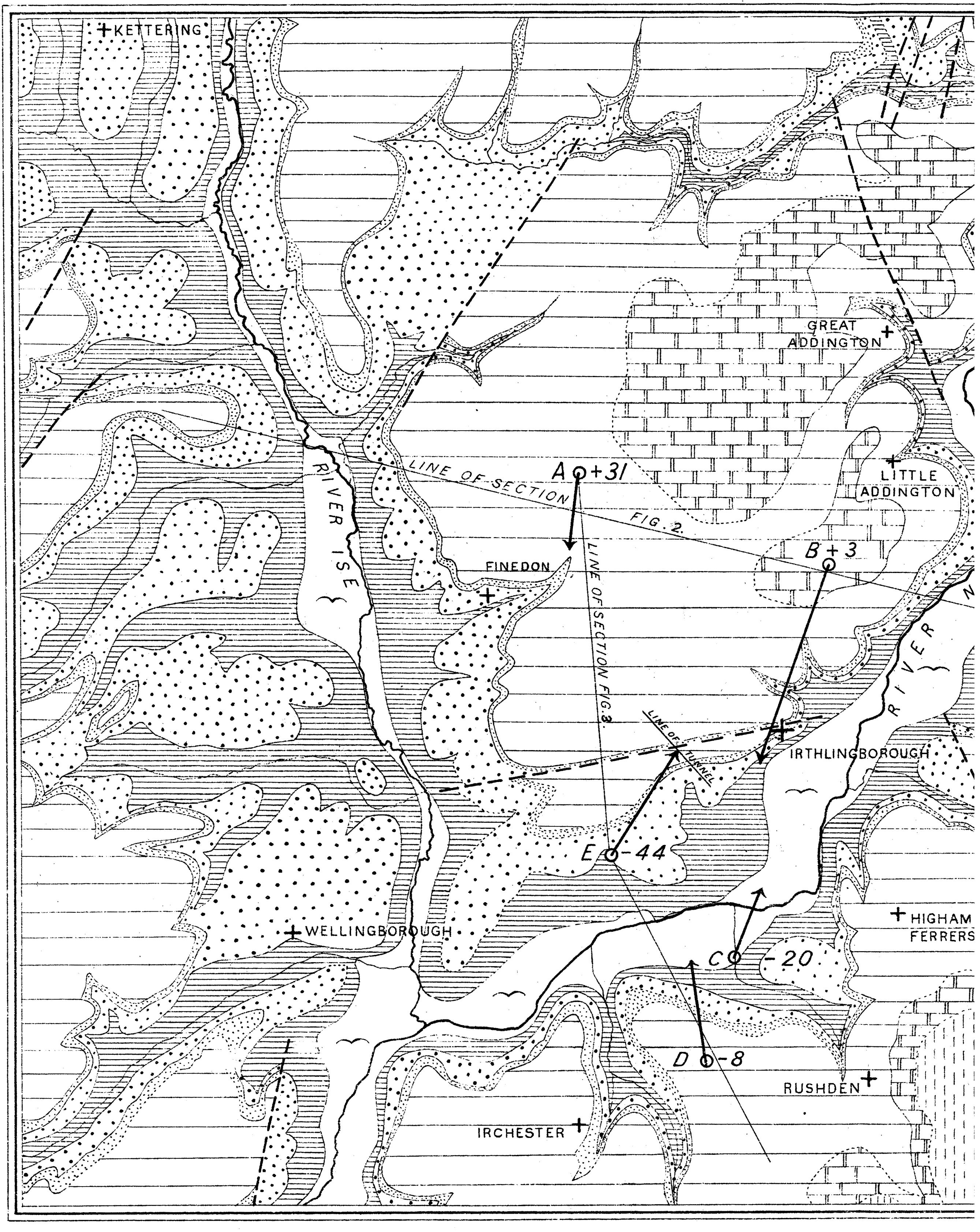
(*b.*) *The Porphyroids* represent altered dacites, that is, andesitic rocks of rather acid composition. They have been described by Prof. BONNEY and Mr. HILL* and by Prof. WATTS.† The specimen tested, from the well-known occurrence at High Sharply, was a typical example. It consists of porphyritic quartz, orthoclase, and plagioclase set in a crypto-crystalline ground-mass showing flow-structure. The phenocrysts often occur as glomero-porphyritic aggregates. The rock is considerably cleaved and altered and the dark minerals, which were only present in small amount, are replaced by epidote and chlorite. Iron-ores are present as minute specks in the ground-mass, and as larger crystals in the glomero-porphyritic aggregates. They are now represented by leucoxene. If any magnetite was present it has been completely altered, with the result that the susceptibility of this rock was much lower than that of any other of the igneous rocks that were tested.

* 'Q. J. G. S.,' vol. XXXIV. (1878), p. 199; vol. XXXVI. (1880), p. 337; and vol. XLVII. (1891), p. 78.

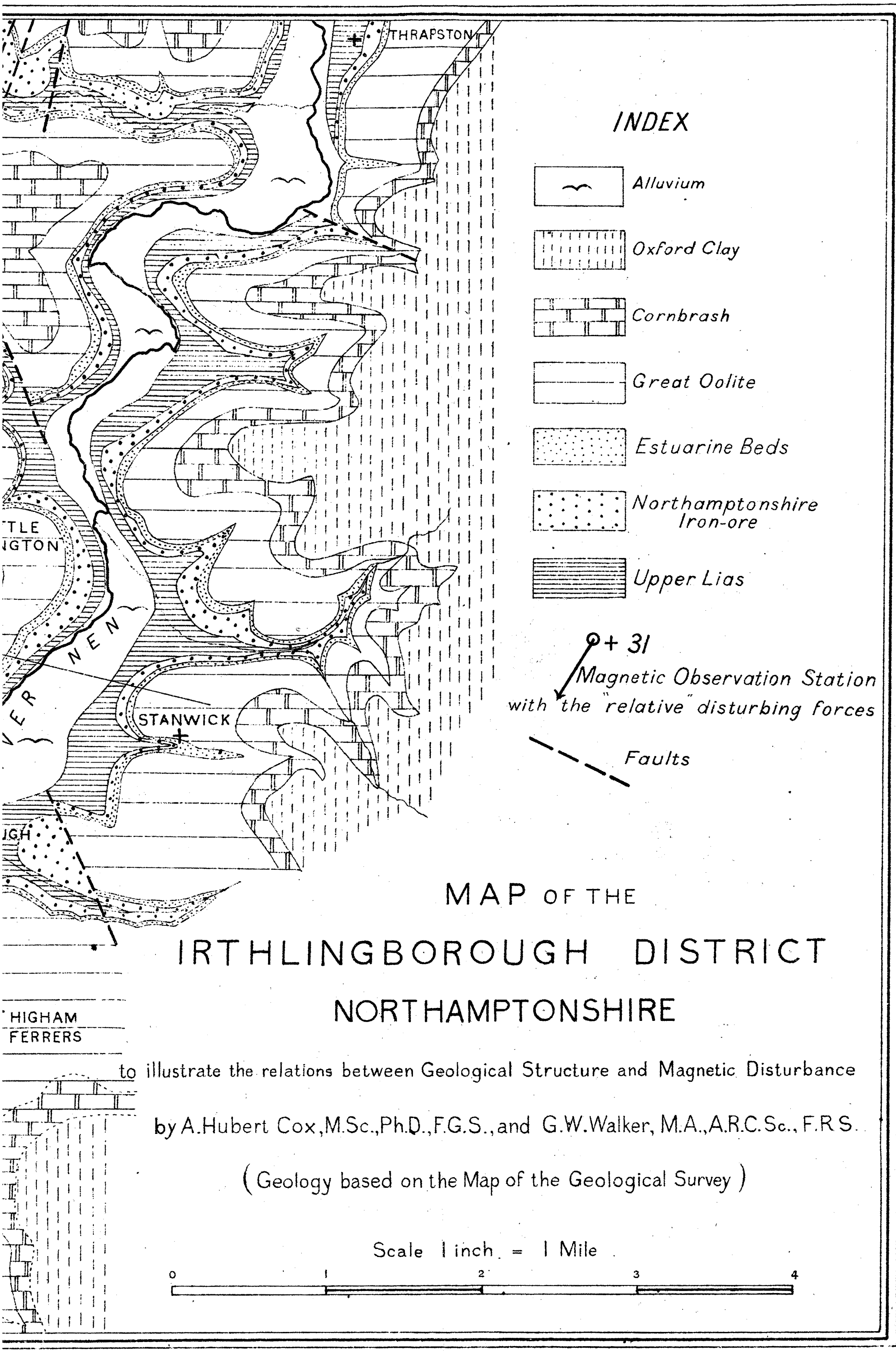
† "The Geology of Burton . . . . . and Loughborough," 'Mem. Geol. Survey,' 1905, p. 8.

Ap. 1.

IRTHLINGBOROUGH
DISTRICT.



KETTERING
GREAT ADDINGTON
LITTLE ADDINGTON
A +31
B +3
LINE OF SECTION FIG. 2.
LINE OF SECTION FIG. 3.
RIVER ISE
FINEDON
LINE OF TUNNEL
IRTHLINGBOROUGH
RIVER N
E -44
C -20
D -8
HIGHAM FERRERS
WELLINGBOROUGH
RUSHDEN
IRCHESTER



MAP OF THE IRTHLINGBOROUGH DISTRICT NORTHAMPTONSHIRE

to illustrate the relations between Geological Structure and Magnetic Disturbance

by A. Hubert Cox, M.Sc., Ph.D., F.G.S., and G.W. Walker, M.A., A.R.C.Sc., F.R.S.

(Geology based on the Map of the Geological Survey)

Ordnance Survey, Southampton, 1919.

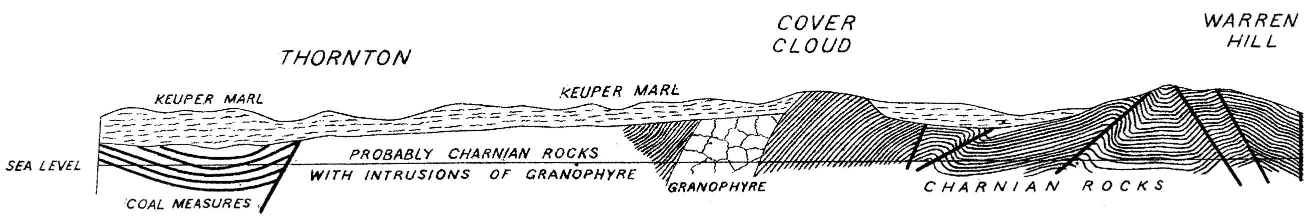
Ap. 2.

SECTION—
LEICESTERSHIRE.

Section across Leicestershire.

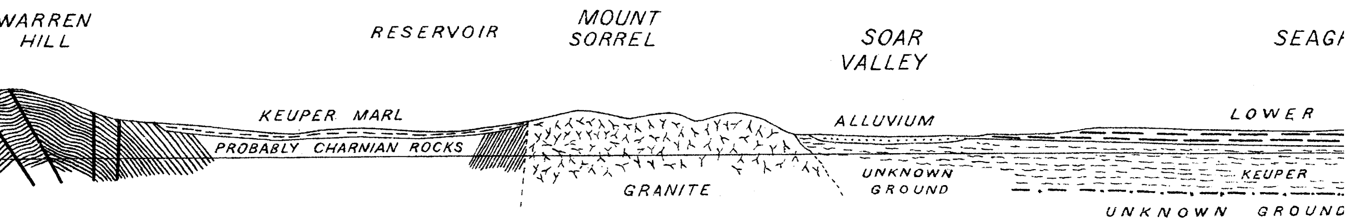
Length of Section 19 miles.

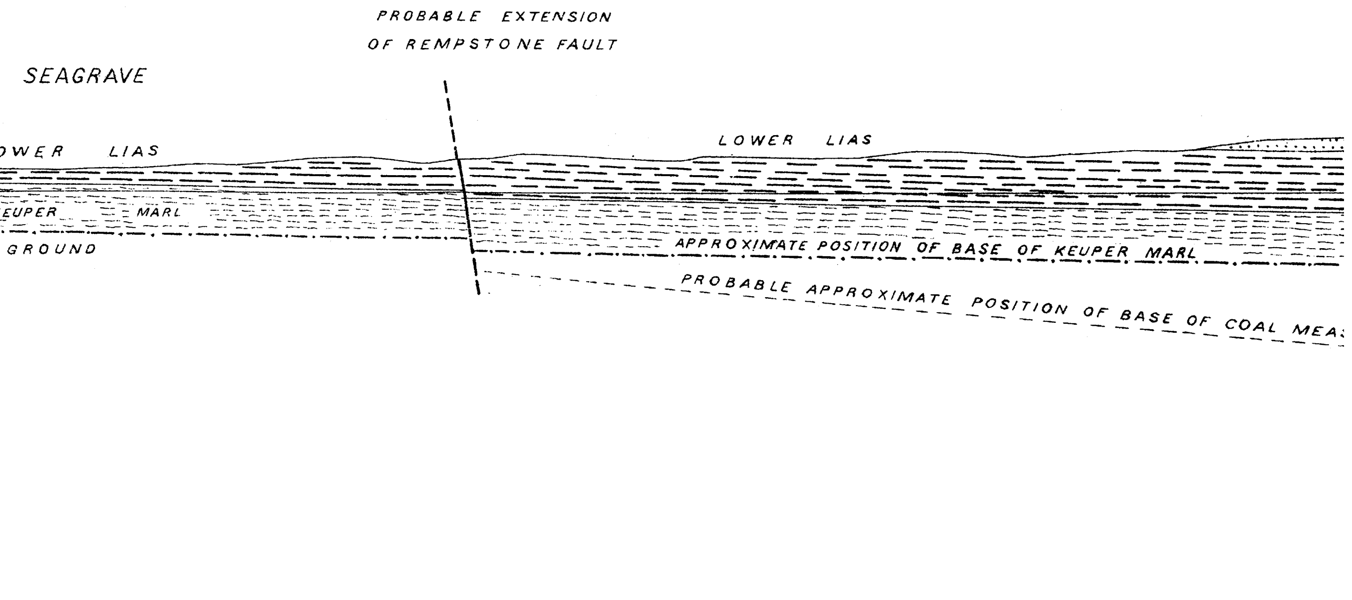
W. 30° S.



Horizontal Scale: 1 inch = 1 mile

Vertical Scale: 3 times the horizontal

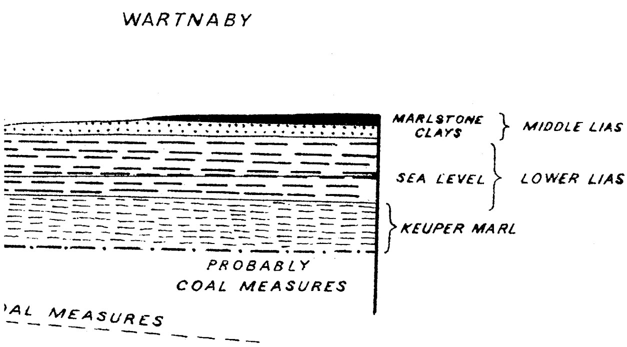

WARREN
HILL
RESERVOIR
MOUNT
SORREL
SOAR
VALLEY
SEAG
KEUPER MARL
PROBABLY CHARNIAN ROCKS
ALLUVIUM
LOWER
GRANITE
UNKNOWN
GROUND
KEUPER
UNKNOWN GROUND



PROBABLE EXTENSION
OF REMPSTONE FAULT
SEAGRAVE
OWER LIAS
LOWER LIAS
EUPER MARL
GROUND
APPROXIMATE POSITION OF BASE OF KEUPER MARL
PROBABLE APPROXIMATE POSITION OF BASE OF COAL MEA

PLATE Ap. 2.

E.30°N.



Ordnance Survey, Southampton, 1919.

Ap. 3.

MAP—
MELTON AND NOTTINGHAM.

MAP OF TH

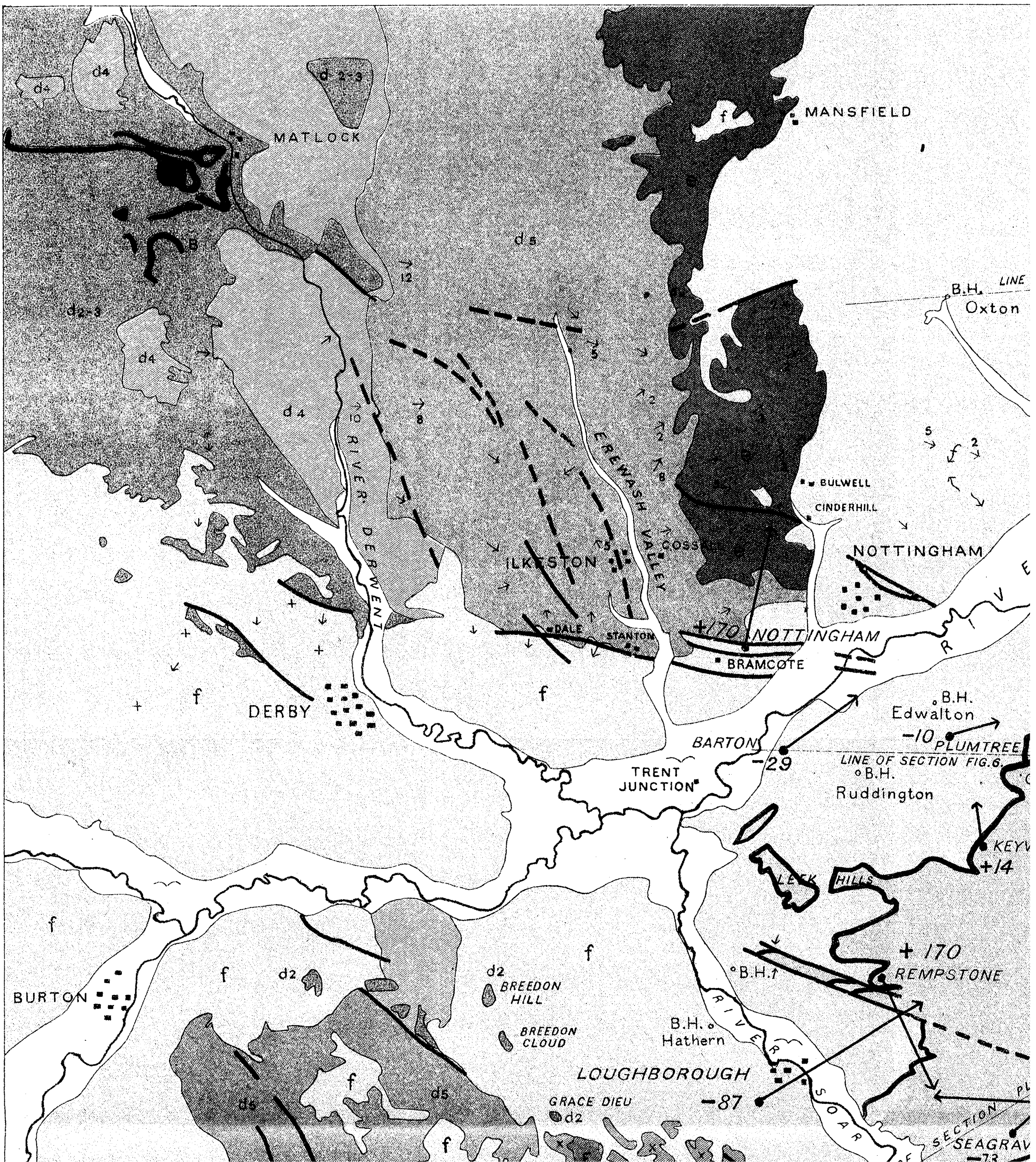
F

MELTON MOWBR

to illustrate the relations between Geol

by A.Hubert Cox, M.Sc., Ph.D., F.G.

(Geology based on the Quarter



OF THE DISTRICT

ROUND

WBRAY AND NOTTINGHAM

een Geological Structure and Magnetic Disturbance

h.D., F.G.S., and G.W.Walker, M.A., A.R.C.Sc., F.R.S.

Quarter inch Map of the Geological Survey)

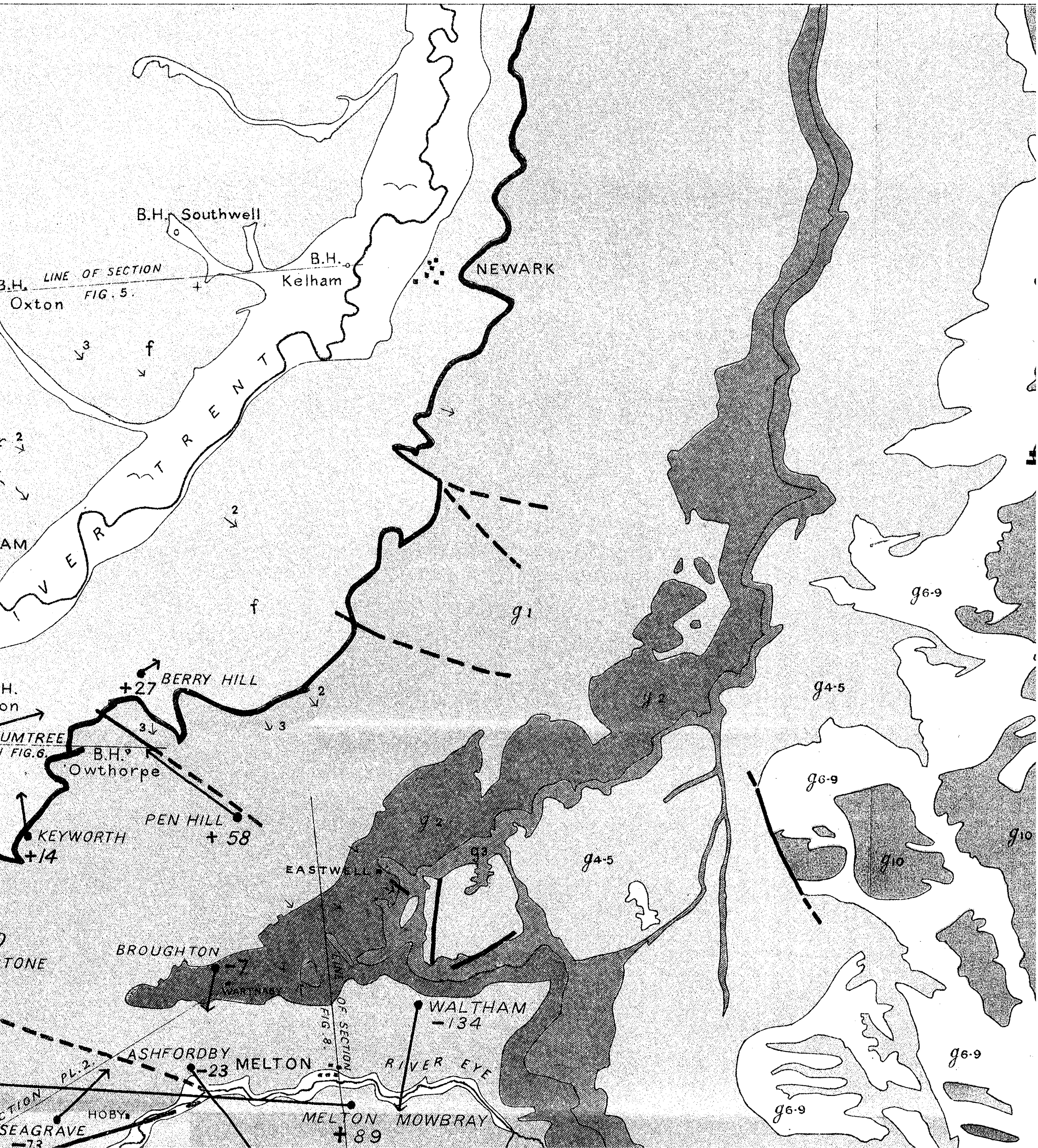
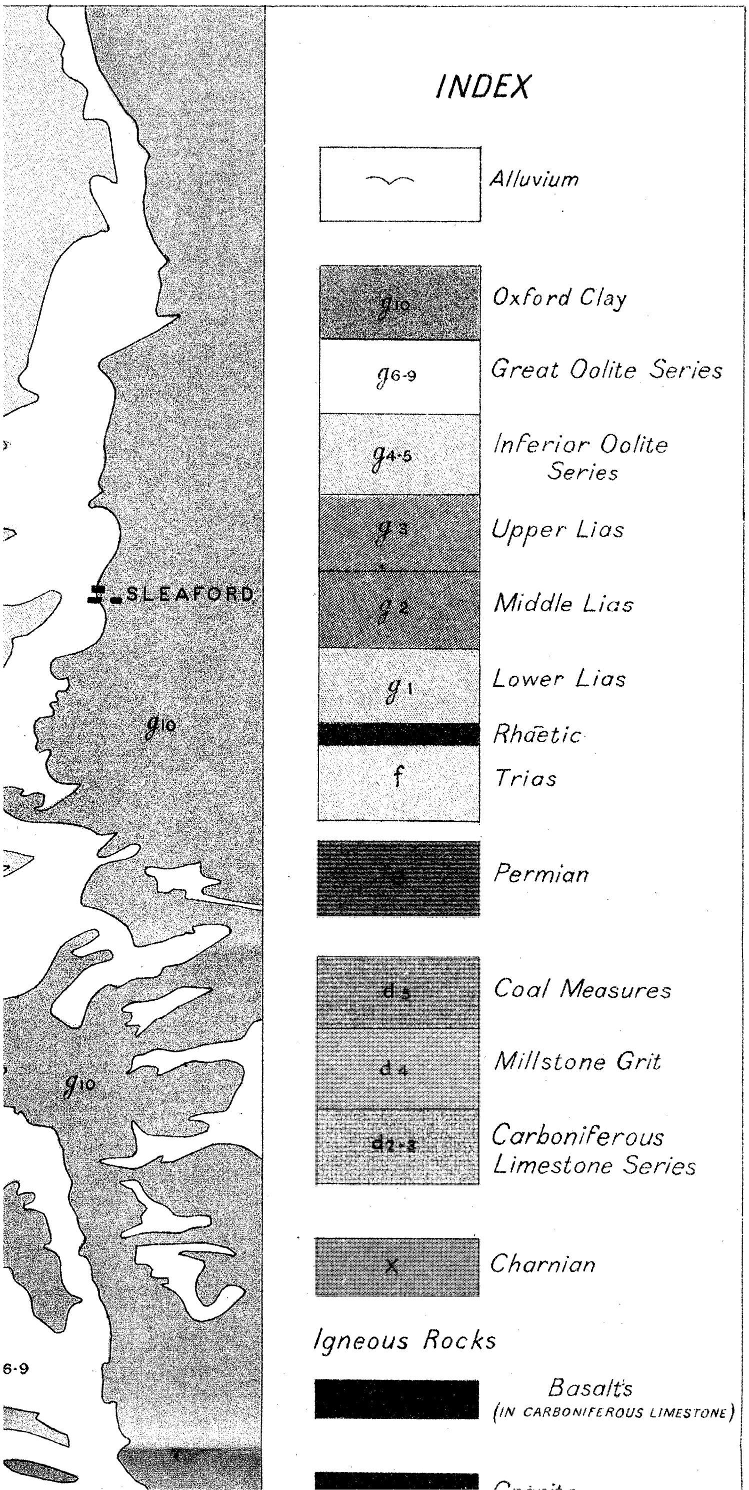
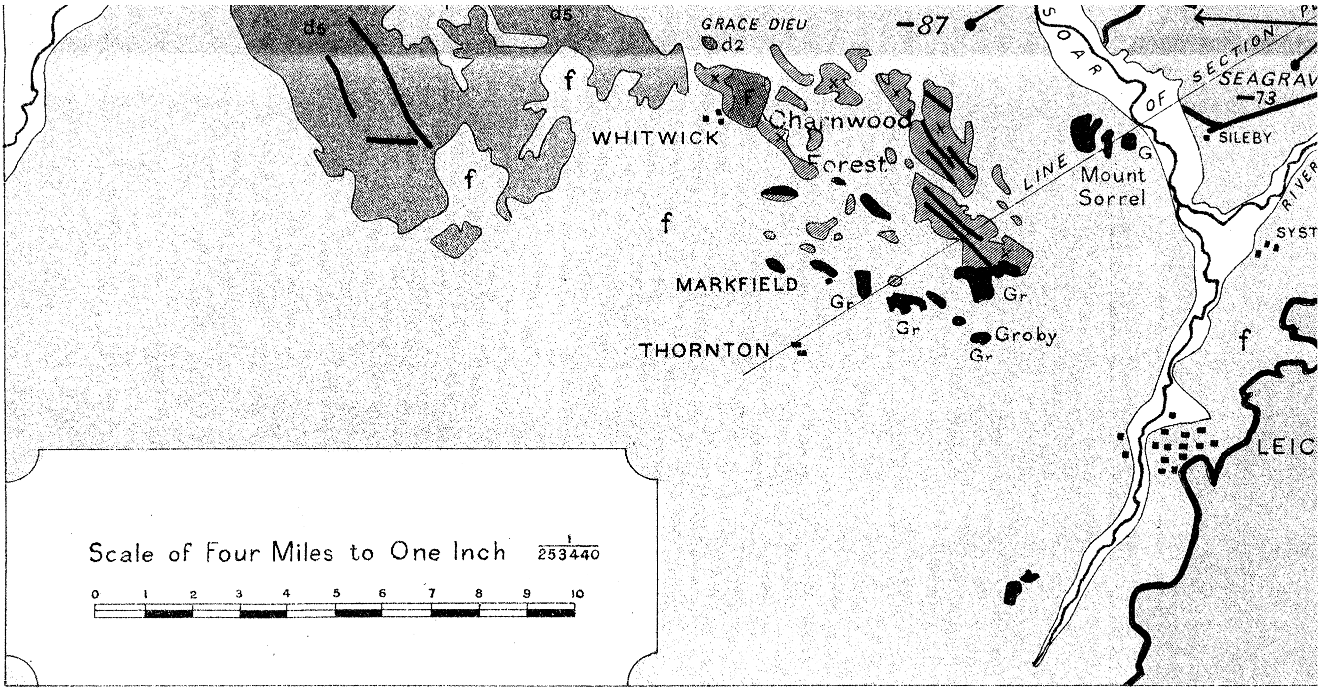
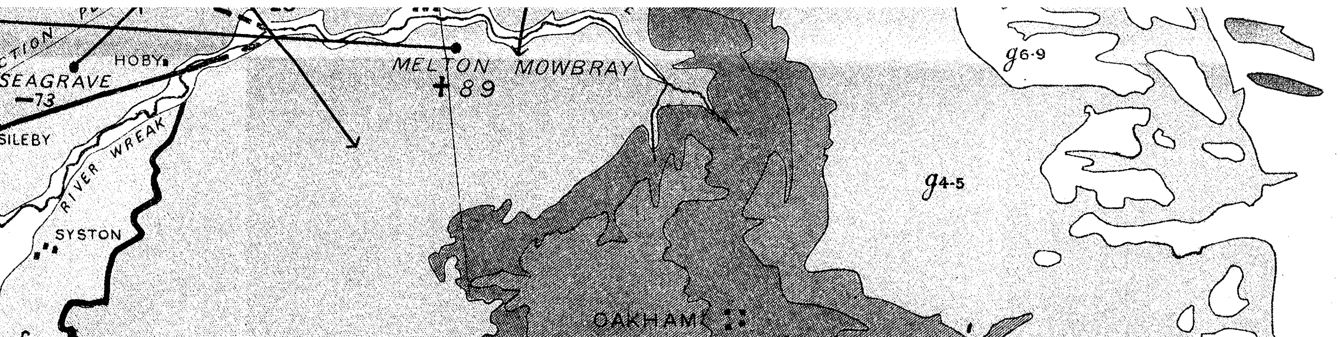


PLATE AP. 3.

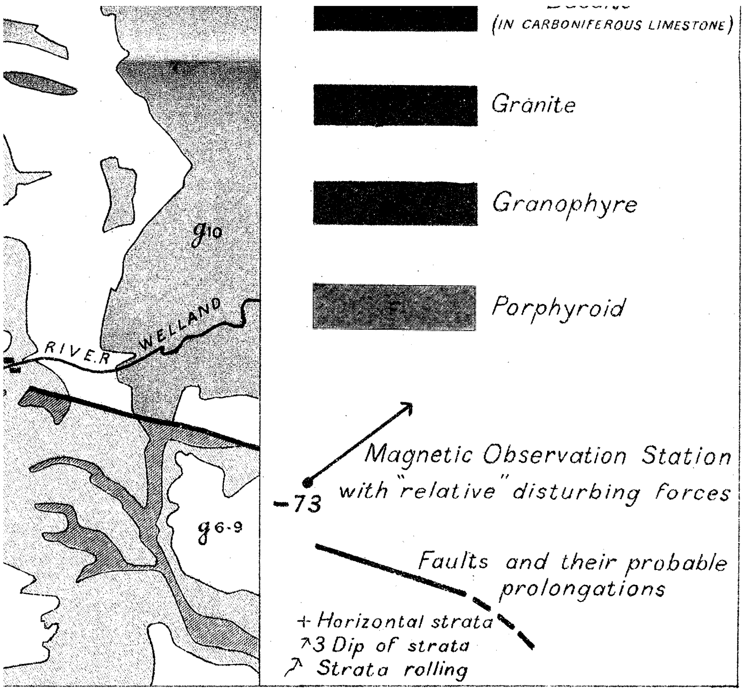

SLEAFORD
g10
g10
6-9
INDEX
Alluvium
g10
Oxford Clay
g6-9
Great Oolite Series
g4-5
Inferior Oolite Series
g3
Upper Lias
g2
Middle Lias
g1
Lower Lias
Rhaetic
f
Trias
Permian
d5
Coal Measures
d4
Millstone Grit
d2-3
Carboniferous Limestone Series
X
Charnian
Igneous Rocks
Basalts
(IN CARBONIFEROUS LIMESTONE)



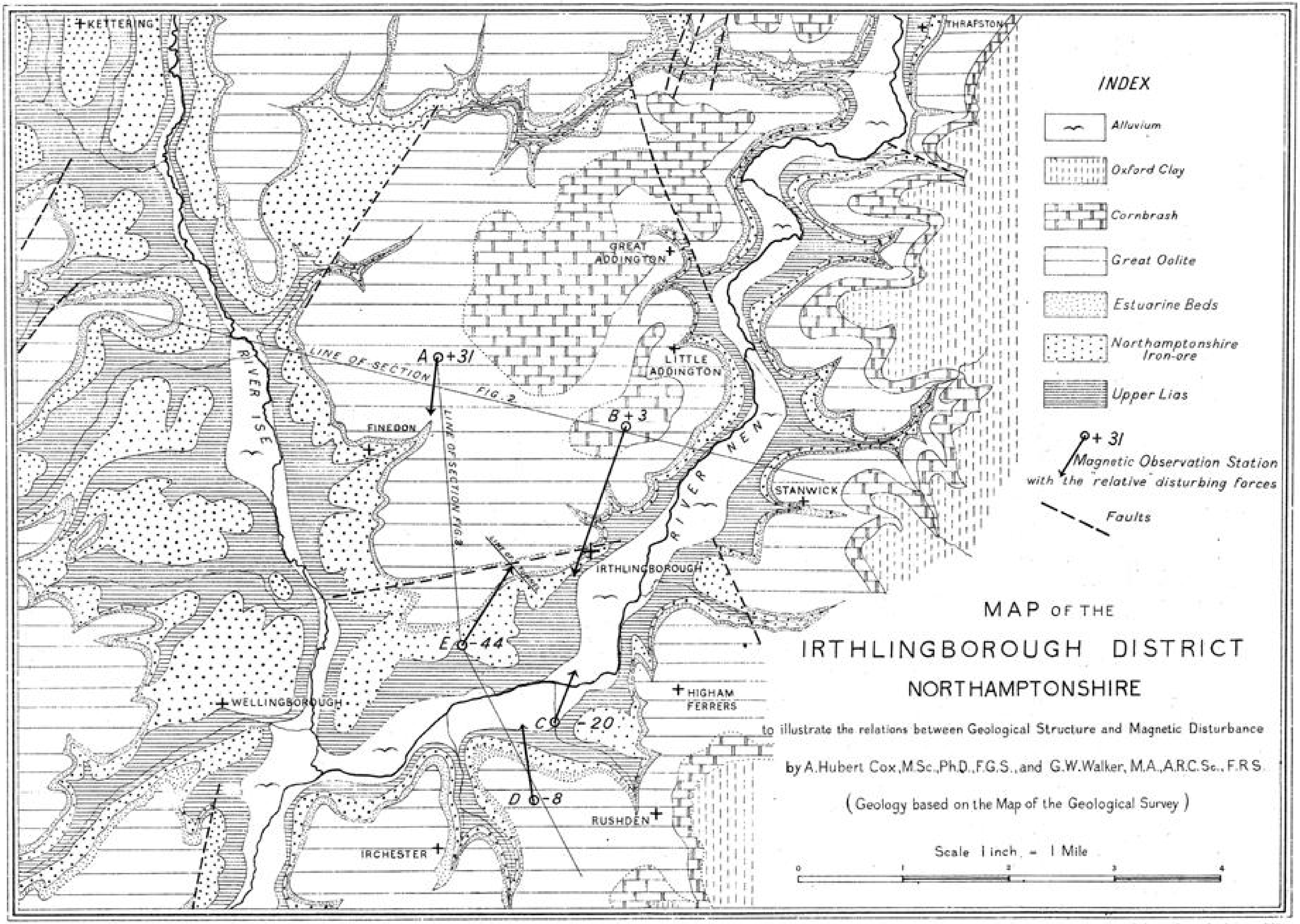
d5
d5
GRACE DIEU
d2
87
f
f
f
f
WHITWICK
Charnwood
Forest
SOAR
LINE OF SECTION
SEAGRAV
73
SILEBY
G
Mount
Sorrel
RIVER
SYST
MARKFIELD
Gr
Gr
Gr
Groby
Gr
THORNTON
f
LEIC
Scale of Four Miles to One Inch
1/253440
0 1 2 3 4 5 6 7 8 9 10



SEAGRAVE
−73
HOBY
SILEBY
RIVER WREAK
SYSTON
MELTON MOWBRAY
+89
f
LEICESTER
g1
g2
g3
OAKHAM
g4-5
g6-9
STAMFORD
RIVE



Ordnance Survey, 1919.

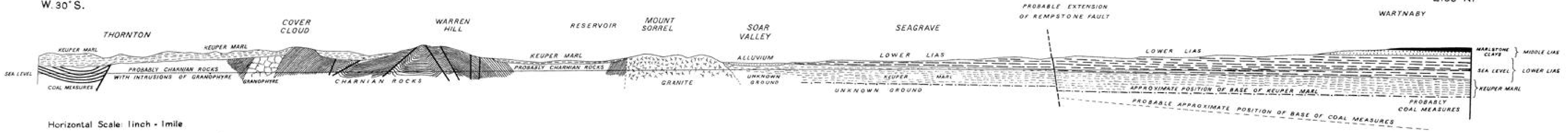


Ordnance Survey, Southampton,

Section across Leicestershire.

Length of Section 19 miles.

PLATE AP. 2.



Horizontal Scale: 1 inch = 1 mile

Vertical Scale: 3 times the horizontal

Ordnance Survey, Southampton. 1919.

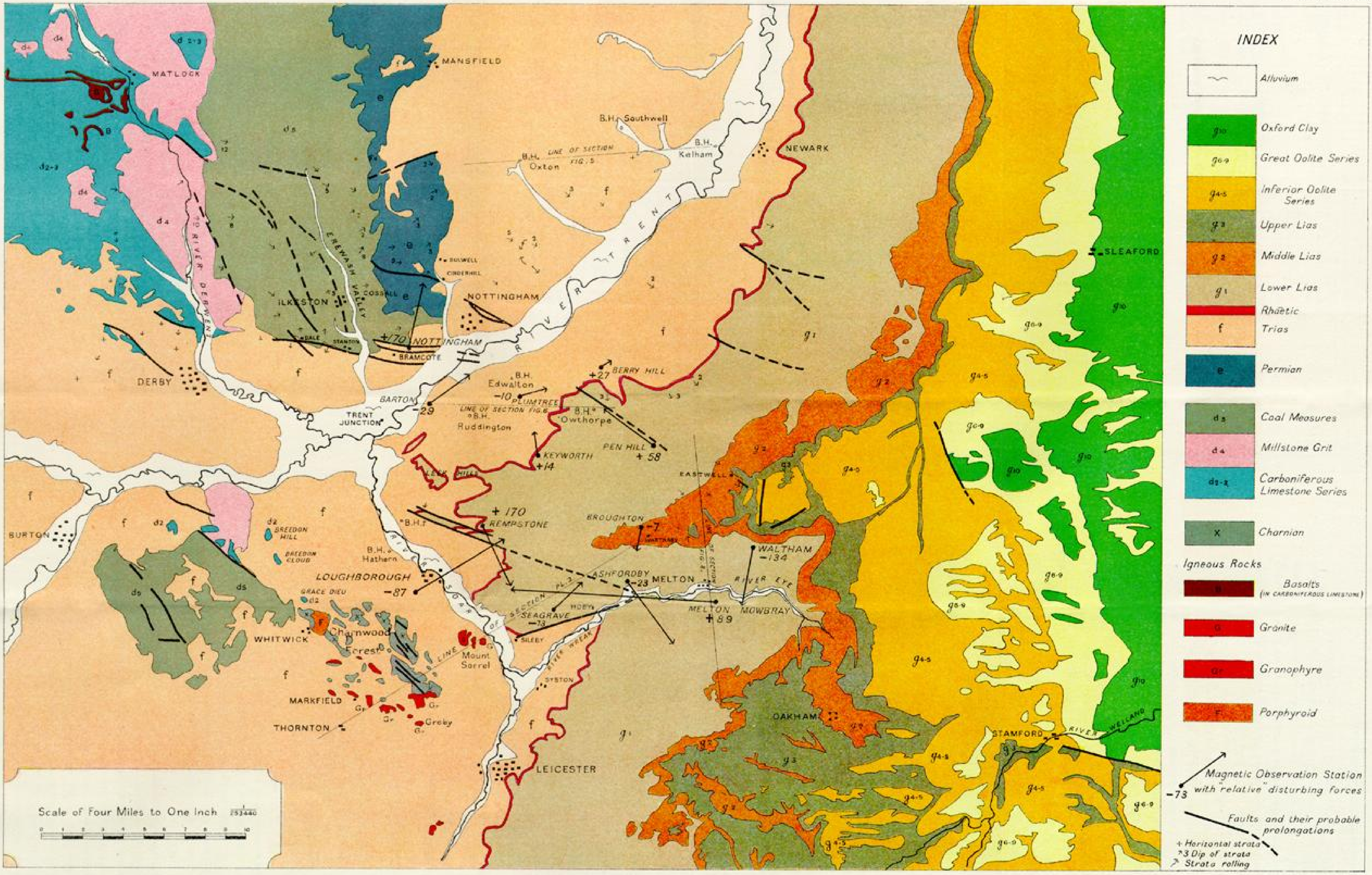
MAP OF THE DISTRICT
ROUND
MELTON MOWBRAY AND NOTTINGHAM

to illustrate the relations between Geological Structure and Magnetic Disturbance

by A. Hubert Cox, M.Sc., Ph.D., F.G.S., and G. W. Walker, M.A., A.R.C.Sc., F.R.S.

(Geology based on the Quarter inch Map of the Geological Survey)

PLATE AP. 3.



Ordnance Survey 1929.

MAP OF T

MELTON MOWBR

to illustrate the relations between Geo

by A. Hubert Cox, M.Sc., Ph.D., F.G.

(Geology based on the Quarter

OF THE DISTRICT
ROUND
OWBRAY AND NOTTINGHAM
veen Geological Structure and Magnetic Disturbance
Ph.D., F.G.S., and G.W.Walker, M.A., A.R.C.Sc., F.R.S.
Quarter inch Map of the Geological Survey)

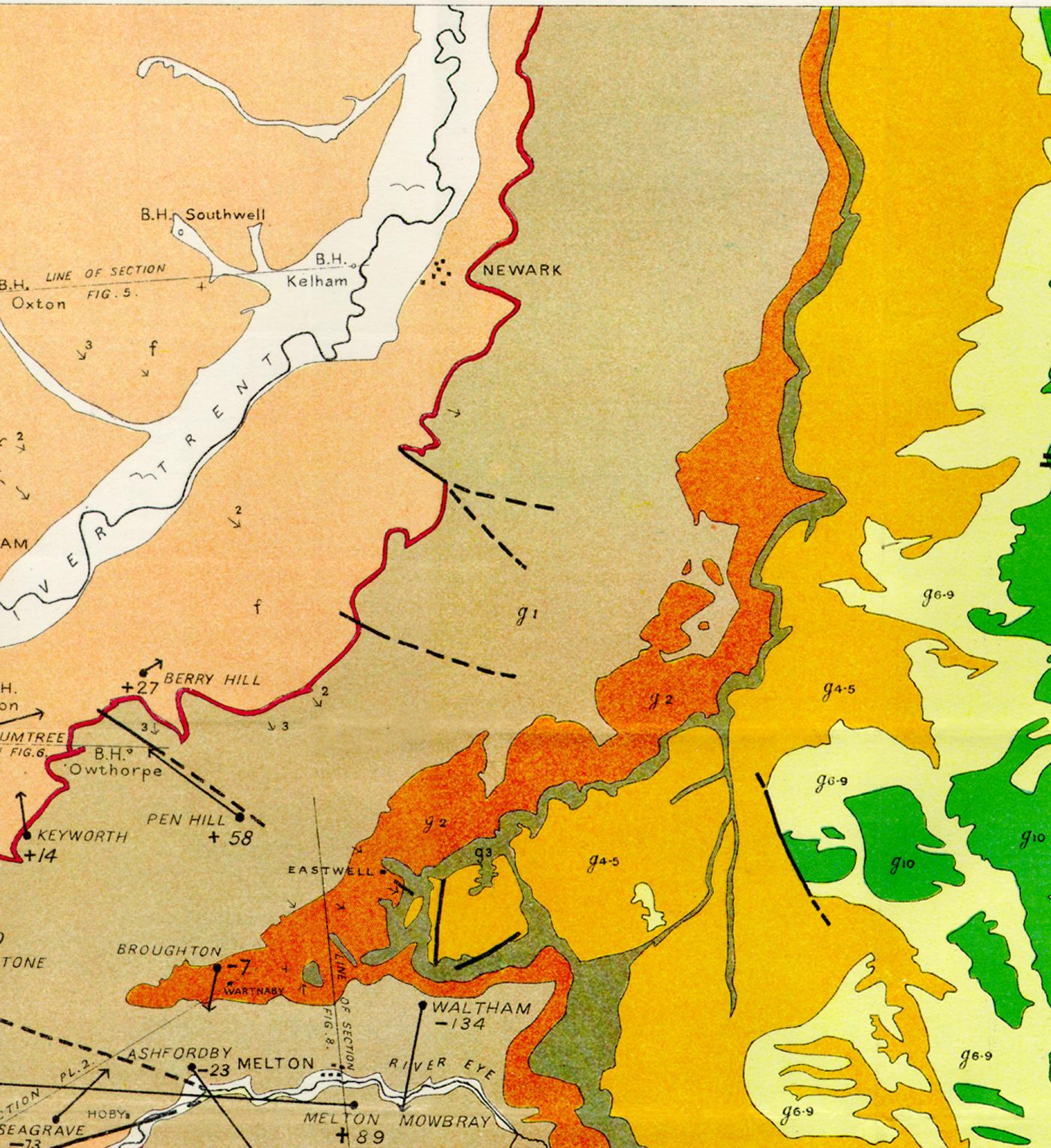
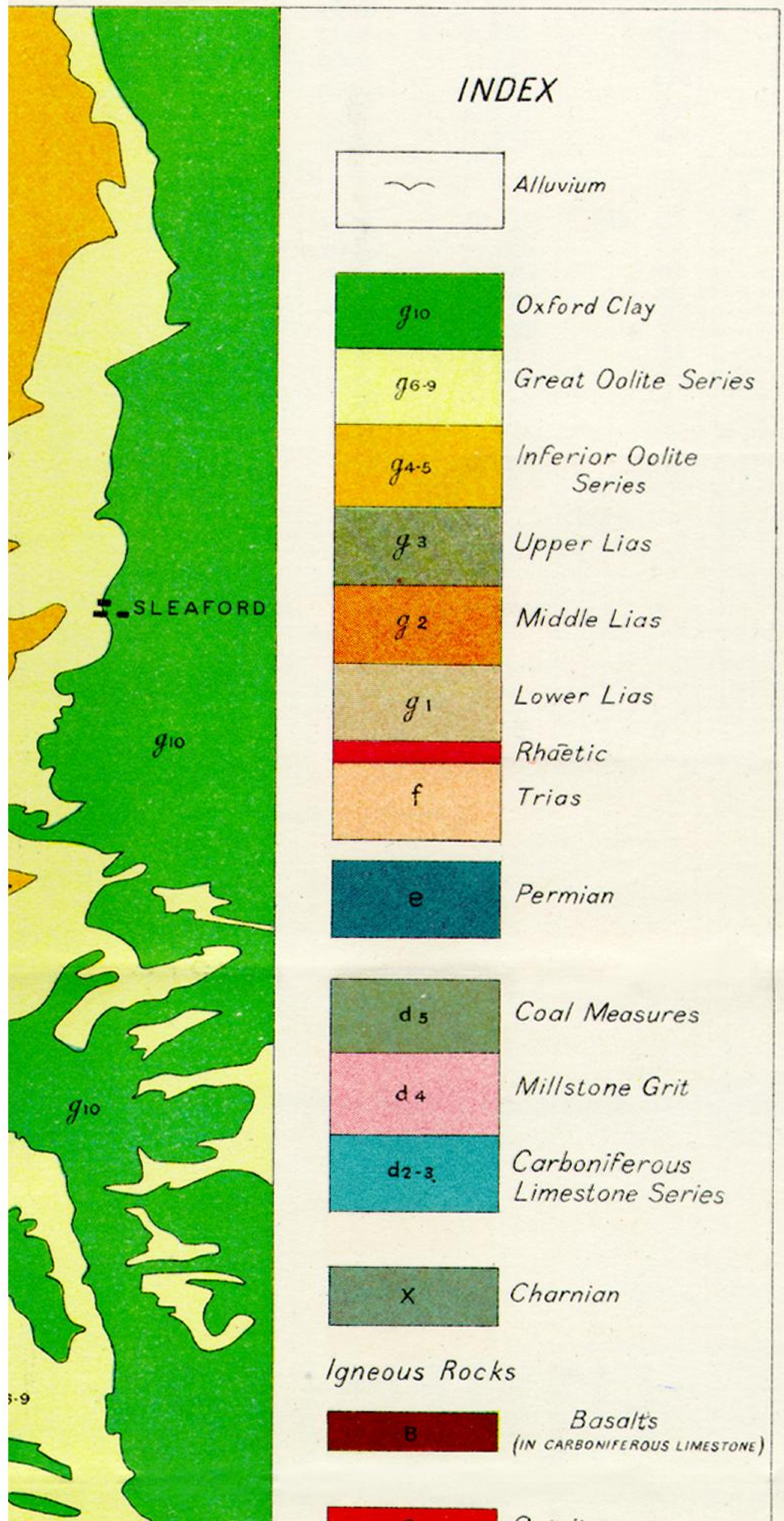
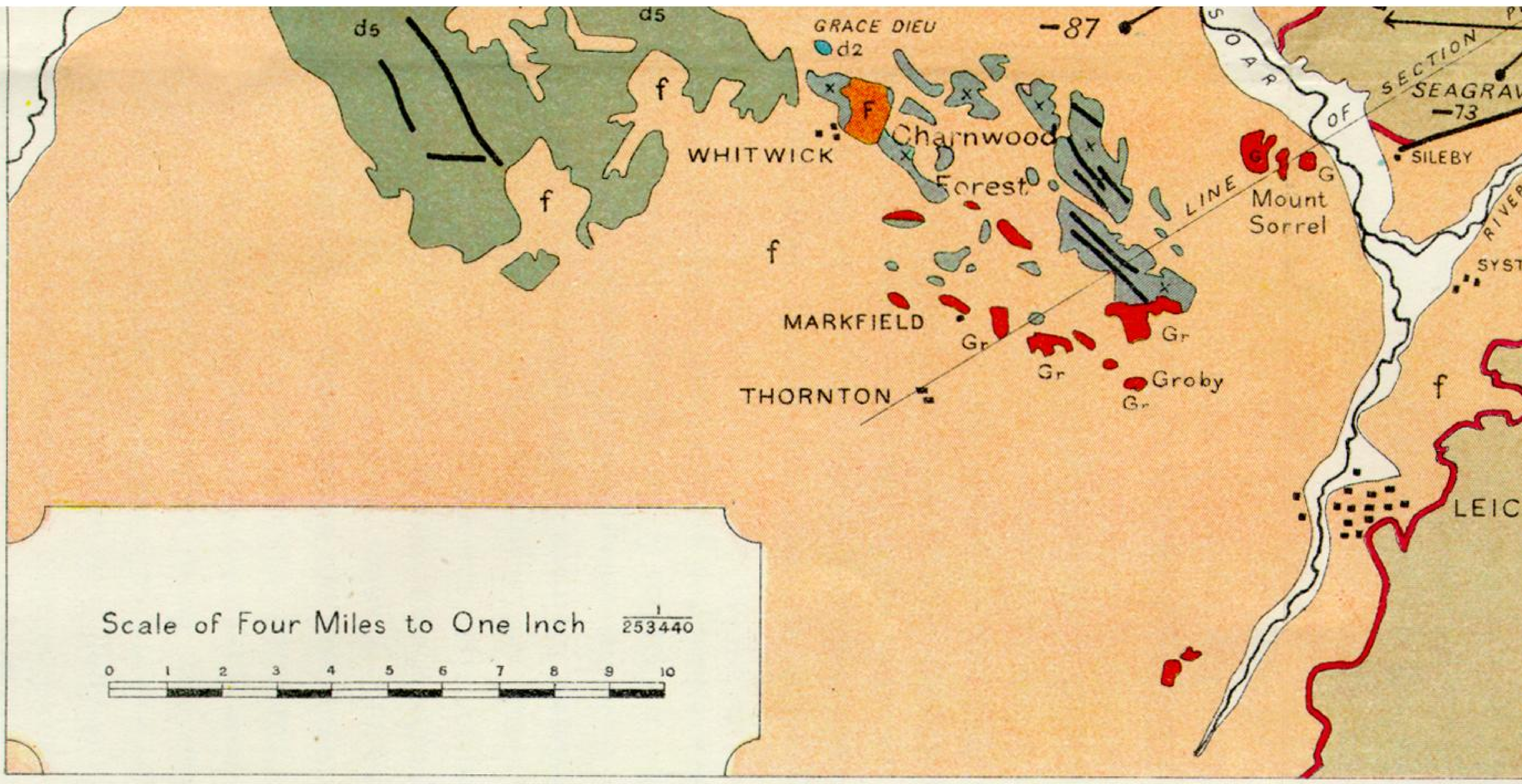
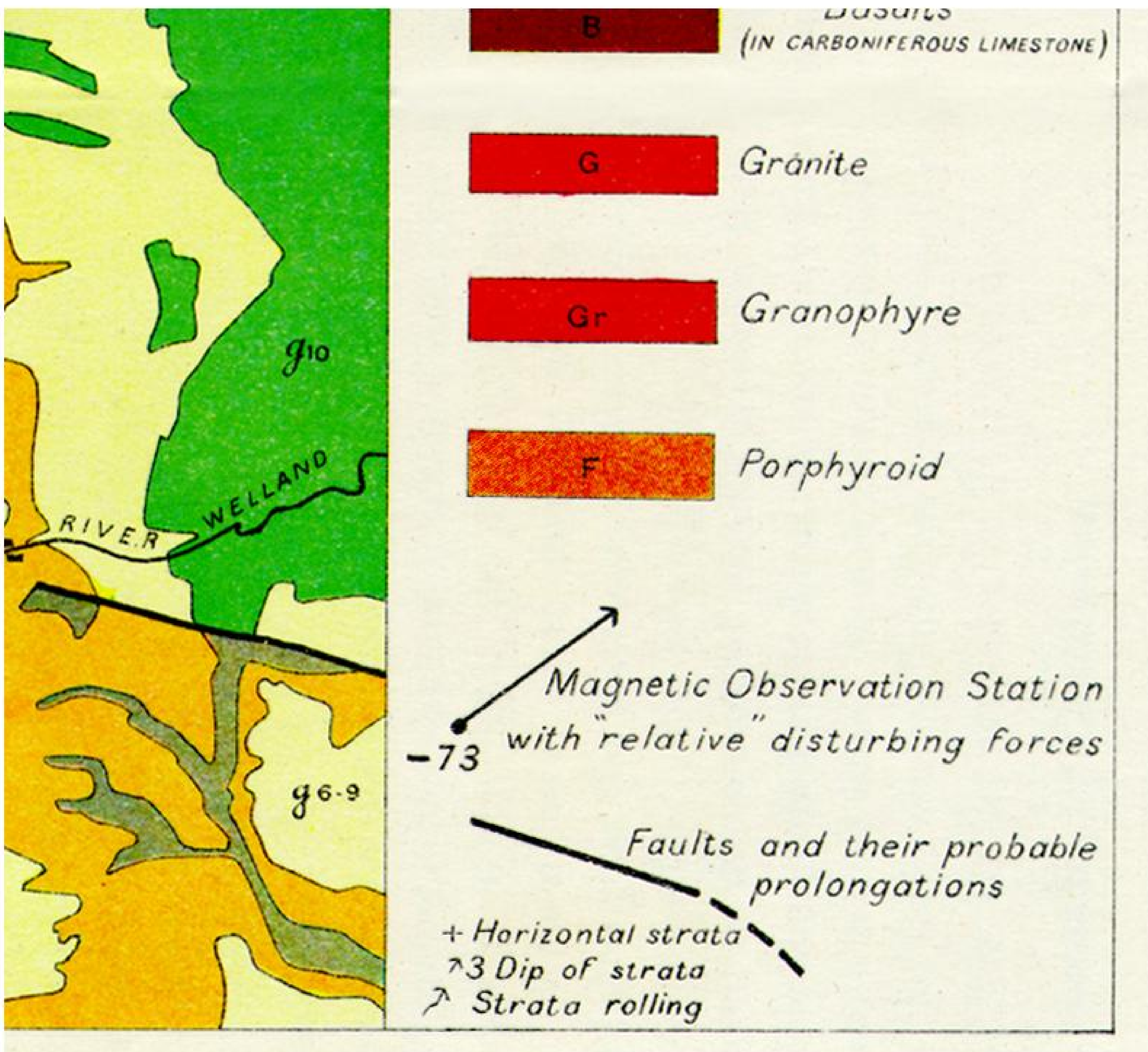


PLATE AP. 3.


SLEAFORD
g10
g10
INDEX
Alluvium
g10
Oxford Clay
g6-9
Great Oolite Series
g4-5
Inferior Oolite Series
g3
Upper Lias
g2
Middle Lias
g1
Lower Lias
Rhætic
f
Trias
e
Permian
d5
Coal Measures
d4
Millstone Grit
d2-3
Carboniferous Limestone Series
x
Charnian
Igneous Rocks
B
Basalts (IN CARBONIFEROUS LIMESTONE)


d5
d5
GRACE DIEU
d2
-87
SOAR
LINE OF SECTION
SEAGRAV
-73
SILEBY
f
F
Charnwood Forest
WHITWICK
G
G
Mount Sorrel
RIVER
SYSTO
MARKFIELD
Gr
Gr
Gr
Groby
Gr
THORNTON
LEIC
Scale of Four Miles to One Inch
1/253440
0 1 2 3 4 5 6 7 8 9 10


SEAGRAVE
-73
HOBY
MELTON MOWBRAY
+89
SILEBY
RIVER WREAK
SYSTON
f
g1
LEICESTER
OAKHAM
g2
g2
g2
g3
g3
g4-5
g4-5
g4-5
g4-5
g4-5
g6-9
g6-9
STAMFORD


B
Basalts
(IN CARBONIFEROUS LIMESTONE)
G
Granite
Gr
Granophyre
F
Porphyroid
Magnetic Observation Station with "relative" disturbing forces
-73
Faults and their probable prolongations
+ Horizontal strata
3 Dip of strata
Strata rolling
g10
RIVER WELLAND
g6-9