SEISMIC INVESTIGATIONS ON THE PALAEOZOIC FLOOR OF EAST ENGLAND

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[Plates 6, 7]

The depth of the Palaeozoic floor under part of east England has been investigated by the refraction seismic method. Records have been taken every 200 ft. along lines 4000–8000 ft. long; such detailed shooting enables various sources of uncertainty in the results to be investigated.

The interpretation of the seismic results required a more thorough knowledge of the contours of the Jurassic and Cretaceous than was available; the data from bore-holes and outcrops have therefore been collected and are presented in the form of contoured maps showing the depths of various horizons and the thicknesses of rock between them.

A map of the form of the Palaeozoic floor and a discussion of its constitution are also given. The latter is based on a re-examination of the bore-hole cores and on the seismic velocities.

CONTENTS

1. Introduction

The investigation of geological problems by the study of the elastic waves from explosions has been widely practised of recent years. Unfortunately, most of the work has been carried out by commercial firms who do not publish detailed accounts of their methods or results. Anyone wishing to use the method has therefore to start practically from the beginning and solve problems many of which have already been solved several times before. To help to remedy this state of affairs the Department of Geodesy and Geophysics of Cambridge University undertook a study of the seismic method. The primary object of this was to develop as simple a technique as possible and to use it to study the problems of the interpretation of the records; the obtaining of geological data in the shortest possible time was of secondary importance. This paper contains a somewhat detailed account of our technique and of the interpretation of the records at particular stations.

On the advice of Professor O. T. Jones we have attempted to map the Palaeozoic floor under east England. The rather scanty bore-hole evidence shows the floor to be composed of a remarkable variety of rocks, Pre-Cambrian felsite, Cambrian shales, Old Red Sandstone, Carboniferous Limestone and Mudstones of doubtful age having all been found within 60 miles of Cambridge. On the worn-down surface of these rocks rest the Jurassic and Cretaceous with an east or south-east dip of less than a degree. The Jurassic consists of clays with a few thin limestones and sands. The thickness at the outcrop is about 1300 ft., but bore-holes show it to thin to the east and to disappear leaving the Cretaceous resting directly on the Palaeozoic. The Cretaceous consists of 100–200 ft. of sand and clay overlain by up to 1000 ft. of chalk.

It was originally hoped to use waves reflected from the Palaeozoic floor, but this was soon found to be impracticable, since it was difficult to separate the reflexions from such a shallow surface from the direct wave, and when satisfactory reflexions could be obtained there was no way of telling whether they came from the Palaeozoic floor or from a higher discontinuity. The refraction method has therefore been used throughout.

2. Apparatus

An account of the construction and characteristics of the geophones used has already been published (Bullard and Kerr-Grant 1938); they are miniature Benioff seismographs in which the gap between a magnet suspended on a spring and an armature fixed to the ground is varied by the motion of the ground. The variations in the flux through the armature cause an electromotive force to be induced in a coil wound round it. The natural frequency of the suspended system is about 30 sec.$^{-1}$, the system being somewhat less than critically damped; the output is 500 V/cm. at 30 cycles. This electromotive force is amplified and applied to an oscillograph. The amplifiers and oscillographs are described in the paper referred to above. Their sensitivity at a frequency of 30 sec.$^{-1}$ is 1000 cm./V at the normal recording distance of 50 cm. Above and below this frequency the response falls off. The magnification of the whole system is 500,000 at its maximum, which occurs at 25 cycles.

The recording is done on fast bromide paper (Ilford Type M) 4 in. wide moving about 20 cm./sec. Records from six geophones are made side by side. The camera is driven by a 6 V D.C. motor. The amplifier oscillographs and camera are mounted in a box 77 × 30 × 37 cm.

The instant of explosion is recorded by the breaking of a wire wrapped round the charge. In the earlier part of the work this wire was connected in series with a battery and a moving-iron oscillograph. The wire for marking the instant of explosion was also used as a telephone line for communication between the recording and the shot points. The chewing of this wire by cows was a source of much annoyance, and at some stations more time was spent in chasing cattle and repairing wire than in any other part of the work. More recently wireless transmitters and receivers have been used instead of the telephones. The transmitters work on 7·5 m. and consist of a pair of Hivac-Harris valves in a push-pull self-excited oscillator. The receiver is a super-regenerative detector followed by a stage of low-frequency amplification. The instant of explosion is transmitted by the breaking of a wire in series with the microphone.

In the earlier part of the work time marks were put on the record by a vibrating spring (period about 0·1 sec.), a slit attached to which allowed light from a flash-lamp bulb to make a mark on the record twice every swing. The period varied by a few parts in a thousand and was calibrated at each station against a break circuit chronometer. In order to avoid this calibration and to give a finer time scale a reed driven by a 100-cycle valve-maintained tuning fork was substituted.

3. Technique

The elastic waves were generated by the explosion of polar ammon-gelignite in shallow bore-holes. The holes were bored with hand tools to such a depth that the explosion produced only slight cracking of the ground. In clay it was found that the depth of hole necessary, D, was related to the charge P by the relation

$$D = 6P^{\frac{1}{3}},$$

where D is in feet and P in pounds.* The holes were tamped with water or with earth. The charge used increased about as the square of the distance, the normal values being

Distance (ft.)	1000	2000	3000	4000	5000	6000	7000	8000
Charge (lb.)	$\frac{1}{4}$	$1\frac{1}{4}$	$2\frac{1}{2}$	$4\frac{1}{2}$	7	10	12	15

The nearer shots were fired first, and from the records given by these it is possible to see if a particular place requires more or less than the normal amount. The use of the correct amount of explosive is important if clear records of the phases after the first arrivals are to be obtained.

The geophones were placed in rubber sponge bags and buried a few inches deep in the ground. They were connected to the amplifiers by a single-core screened cable, the screen being used as a return lead. The recording apparatus was normally used in a van which also served as a dark room for developing the records.

Before the screened cable was introduced great trouble was experienced from electrical disturbances. These were of three kinds: firstly, the cable picked up wireless atmospherics and field changes due to nearby thunderstorms; secondly, wind caused movements of

* $D = 2{\cdot}4P^{\frac{1}{3}}$ for metres and kilograms.

the cable in the earth's electrostatic field which caused changes in the potential of the grid of the first valve of the amplifier; thirdly, leakage from power cables occasionally gave trouble. The first two were completely eliminated by the use of screened cable. The third was eliminated by connecting the geophone case to the screen.*

The six instruments were usually placed 200 ft. apart and shots fired every 1000 ft. The farthest geophone is then at the same distance from one explosion as the nearest geophone is from the next; this overlap between successive shots provides a useful check.

4. Methods of interpretation

The elementary theory of the refraction method assumes that the medium consists of homogeneous layers of rock, the velocity in each layer being greater than in that above. Rays such as those in figure 1 are then considered.

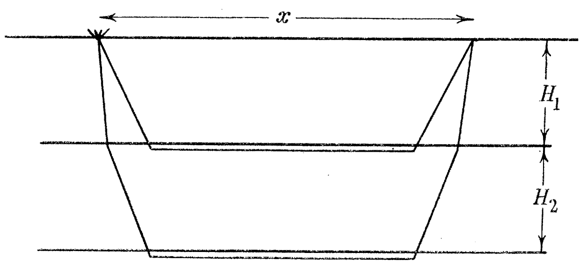


Figure 1. Paths of rays.

Let the time of transmission t over a distance x of the ray reaching the nth layer be

$$t = t_n + x/v_n, \tag{1}$$

where $v_1, v_2, \ldots, v_n$ are the velocities in the various layers. It may be shown from Snell's Law that the constants $t_1, t_2, \ldots, t_n$ are given by

$$\left.\begin{aligned} t_1 &= 0, \\ t_n &= \sum_{s=1}^{n-1} \frac{2H_s}{v_s} \sqrt{\left(1 - \frac{v_s^2}{v_n^2}\right)}, \end{aligned}\right\} \tag{2}$$

where $H_1, H_2, \ldots, H_{n-1}$ are the thicknesses of the layers. The constants $v_1, v_2, \ldots, v_n$, $t_2 \ldots t_n$ can be determined from the time-distance measurements on the various pulses and (2) solved for $H_1 \ldots H_{n-1}$. In the present work we have usually a low-velocity surface layer, one or more layers of Mesozoic rocks with comparatively small changes in velocity between them, and underneath them an indefinite thickness of Palaeozoic or Pre-Cambrian rocks with a velocity much greater than that in the Mesozoic. The top surface of the latter is the Palaeozoic floor and will be referred to as "the interface" in the discussion that follows.

* The sponge bags provide a high resistance path between the case and earth. Without them disturbances can still sometimes be noticed due to the resistance of the cable not being negligible. Insulating both leads from the case is quite ineffective as there is a considerable capacity between the case and the grid lead. The sponge bags also serve to keep rain off the terminals.

As the time-distance curves are approximately straight lines, as many linear expressions as seemed convenient were fitted to them by least squares and the residuals calculated. Systematic trends in these residuals indicate departures of the actual rocks from the homogeneous horizontal layers assumed in the simple theory. Such departures may cause the calculated depths to be much more in error than would be expected from a discussion of the residuals, assuming the simple theory to be correct. We therefore consider the effect of various departures from the above assumptions.

(*a*) *Slope of the interface.* If a layer of velocity v_1 overlies one of higher velocity v_2 and the interface between them dips at an angle α to the horizontal, it may be shown that the time-distance curves obtained from a fixed geophone and shots at various distances down dip, is the straight line

$$t = \frac{2H\cos\alpha}{v_1}\sqrt{\left(1-\frac{v_1^2}{v_2^2}\right)}+\frac{x}{v_1}\sin(\theta+\alpha), \tag{3}$$

where $\sin\theta = v_1/v_2$, and H is the depth of the interface below the geophone. For shots up dip the last term has $\sin(\theta-\alpha)$. Thus by shooting in both directions it is possible to determine H, v_2, and α. For the small dips met with in this work it may be shown from (3) that to a sufficient approximation

$$\left.\begin{aligned} \frac{2}{v_2} &= \frac{1}{U_1}+\frac{1}{U_2}, \\ 2\alpha &= v_1\left(\frac{1}{U_1}-\frac{1}{U_2}\right)\Big/\sqrt{\left(1-\frac{v_1^2}{v_2^2}\right)}, \\ 2H &= v_1 t_2\Big/\sqrt{\left(1-\frac{v_1^2}{v_2^2}\right)}, \end{aligned}\right\} \tag{4}$$

where U_1 and U_2 are the apparent velocities down and up dip and t_2 is the intercept of the time-distance curve on the time axis. If a number of geophones are used to record each shot and the shot is down dip from the geophones, the velocity derived from the record of any one shot at all the geophones will be $v_1/\sin(\theta-\alpha)$, whilst that from all the shots at any one geophone will be $v_1/\sin(\theta+\alpha)$. It is therefore possible to determine H_1, v_2 and α from shots in a single direction only, though the standard errors will be greater than when the line is shot in both directions. The type of time-distance curve to be expected is shown in figure 2*a*.

If a linear function $$t = t_2+x/U$$

be fitted by least squares to a set of n observations evenly spaced along a line of length l, it may be shown that the standard error of $1/U$ is

$$\delta\left(\frac{1}{U}\right) = \frac{\sigma}{l}\sqrt{\frac{12(n-1)}{n(n+1)}} \doteq \frac{\sigma}{l}\sqrt{\frac{12}{n}} \quad \text{if } n \text{ is large,}$$

where σ is the standard error of a single observation. Thus if we shoot a line of length l in both directions, using m geophones and making s shots, we obtain standard errors for α and v_2

$$\delta\alpha = \frac{v_1\sigma}{l}\sqrt{\frac{6(ms-1)}{ms(ms+1)(1-v_1^2/v_2^2)}}, \qquad \frac{\delta v_2}{v_2} = \frac{v_2\sigma}{l}\sqrt{\frac{6(ms-1)}{ms(ms+1)}}.$$

If the U_2 of (4) is obtained from the mean of the velocities given by the individual shots treated separately, the standard errors of α and v_2 are almost entirely due to the uncertainty of U_2 and

$$\delta\alpha = \frac{v_1\sigma}{l}\sqrt{\frac{3s(m-1)}{m(m+1)(1-v_1^2/v_2^2)}}, \qquad \frac{\delta v_2}{v_2} = \frac{v_2\sigma}{l}\sqrt{\frac{3s(m-1)}{m(m+1)}}.$$

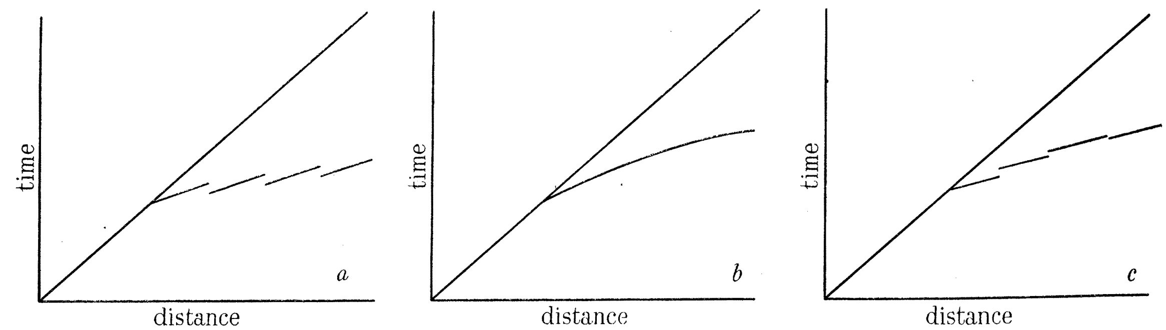


FIGURE 2. Types of time-distance curves given by (a) a sloping interface, (b) an increase in velocity with depth, and (c) a concave interface.

The second determination of α and v_2 has a standard error approximately $s/\sqrt{2}$ times larger than the first. To take a numerical example let $v_1 = 7000$, $v_2 = 14{,}000$ ft./sec., $l = 4000$ ft., $m = 6$, $s = 4$, and $\sigma = 20 \times 10^{-4}$ sec., then for a line shot in both directions

$$\delta\alpha = 0{\cdot}11^\circ, \qquad \delta v_2/v_2 = 0{\cdot}35\,\%,$$

for a line shot in one direction

$$\delta\alpha = 0{\cdot}31^\circ, \qquad \delta v_2/v_2 = 1{\cdot}0\,\%.$$

The uncertainty of the results obtained by shooting one way is therefore usually less than that which will be caused by geological irregularities. The value of H obtained from (4) is hardly affected by errors in v_1 and v_2, and the standard errors of the depths obtained by the two methods will only differ by the factor $\sqrt{2}$ due to the greater number of observations taken when shooting both ways.

If an appreciable slope is found by shooting in one direction the result must be regarded with some reserve, for an identical time-distance curve would be produced by a slope twice as great under the geophones and no slope under the rest of the line. Such ambiguities can only be cleared up by shooting overlapping lines in both directions. The finding of a large slope by shooting in one direction is therefore to be regarded as a sign that more detailed work is necessary if correct velocities and slopes are required; the advantage of the technique is that it avoids the necessity for shooting in both directions at the great majority of stations where no slope is found.

In the present work the largest slope found is 3·9°, and most of the lines have therefore only been shot in one direction. At each station the residuals from the best straight-line solution for the refracted wave are found, and the means for all the arrivals at the individual geophones calculated. The mean for the first three geophones is then subtracted from the mean for the second three, and the difference compared with its standard error, computed from the standard error for a single observation found from the final residuals for a group of stations (see § 5).* If a significant difference is found a line is fitted by least squares to the means for the six geophones; the velocity found from this line is the U_2 of equation (4). The means for the arrivals at all the geophones of the waves from the individual shots are then found and a straight line fitted to them. The velocity found from this line is U_1 in equation (4), and its intercept on the t axis is t_2. The slope found is, of course, not the true angle of dip but its component along the seismic line; to determine the true dip it would be necessary to shoot another line at an angle to the first. This has not been done at any of the stations in the present work and the slopes given are only the components along the line.

A wedge-shaped surface layer of low velocity will have the same effect on the time distance relation for the refracted wave as a slope in the interface. A case occurring in the present work is a layer of glacial sand about 10 ft. thick with a velocity of 1000 ft./sec. overlying chalk about 500 ft. thick with a velocity of 7500 ft./sec. resting on the Palaeozoic with a velocity of 16,000 ft./sec. If the sand is a wedge of angle α the time-distance relation for the refracted ray will indicate a spurious slope of 12α in the Palaeozoic floor. Irregular variations in thickness will increase the scatter of the observed points. These errors may be eliminated by determining the thickness of sand at each geophone and shot point. This may be done by boring, or by firing a small charge near the surface at each end of the geophone line and shooting short lines near each shot point. The latter method is the better as it determines the time taken in the surface layer directly. Let $1, 2, \ldots, N$ be the positions of N geophones, and let there be a surface layer of variable depth and velocity resting on homogeneous rock of velocity v. We wish to reduce the times to those that would have been obtained if the upper layer had been removed and the geophones rested on the rock beneath. If the velocity in the surface layer is considerably less than in the material below, the rays in the former will be nearly vertical and, as the time for the actual path is a minimum, a negligible error will be made by assuming them exactly vertical (for 10 ft. of material giving a velocity of 1500 ft./sec. overlying a material giving 6000 ft./sec. the error is always less than 0·0002 sec.). If $t_1, t_2, \ldots, t_N$ are the times spent in the surface layer, the times of transmission $T_2, T_3, \ldots, T_N$ from a shot at 1 to geophones at $2, 3, \ldots, N$ are

$$\begin{aligned} T_2 &= t_1+t_2+x_2/v, \\ T_3 &= t_1+t_3+x_3/v, \\ &\cdots\cdots\cdots\cdots \\ T_N &= t_1+t_N+x_N/v, \end{aligned}$$

* The standard error computed from the residuals being tested must not be used, as if there is a slope these will be larger than the random errors.

and those T'_1, T'_2, ..., T'_{N-1} from a shot N to geophones 1, 2, ..., $(N-1)$ are

$$\begin{aligned} T'_1 &= t_1+t_N+x_N/v, \\ T'_2 &= t_2+t_N+(x_N-x_2)/v, \\ &\dots\dots\dots\dots \\ T'_{N-1} &= t_{N-1}+t_N+(x_N-x_{N-1})/v. \end{aligned}$$

If an approximate value of v is known from more distant shots these $2(N-1)$ equations determine the N constants t_1, t_2, ..., t_N.

(*b*) *Increase of velocity with depth below the interface.* If the velocity increases with depth below the interface the time-distance curve will not be a straight line and there will be ambiguity in the extrapolation to zero distance that is necessary to find the time spent in traversing the upper layers. If the general form of the variation of velocity with depth were known the form of the travel-time curve could be calculated and the parameters adjusted to fit the observed points. Actually the curvature of the time-distance curve is always small, and we may therefore assume that the variation of velocity with depth is slow and the simplest assumption is to take a linear variation with the depth z below the interface,

$$v = v_2(1+\beta z). \tag{5}$$

The time-distance curve will then be* (Lehmann 1937, p. 255), to the first order in β,

$$t = t_2+x/v_2+Ax^3, \tag{6}$$

where $$A = \beta^2/24v_2.$$

The depth below the interface reached by the refracted ray is $\frac{1}{8}\beta X^2$, where X is the horizontal distance travelled below the interface.

No term in x^2 can occur in (6) if dv/dz is finite at the interface. The depth can be calculated from t and v by the use of (2), which may be shown to be correct to a sufficient approximation even when there is an increase of velocity with depth below the interface.

The residuals from the straight-line solution for the refracted wave were tested for curvature by dividing them into three groups covering equal ranges of distance. The mean of the first and third groups was subtracted from that of the middle group, and the difference compared with that to be expected from the standard error of a single observation determined from the residuals from a group of stations (§ 5). Some care is necessary in interpreting such curvatures, for variations in the thickness of a superficial low-velocity layer, or curvature in the form of the Palaeozoic floor, will have a similar effect on the time-distance curve. In principle, it is possible to separate these effects if, as in the present work, a line of geophones remains in the same place for each shot and the shot point is moved. The distinction is illustrated in figure 2, where (*b*) shows the result to be expected from an increase in velocity with depth and (*c*) shows that produced by a curvature of the interface. In practice the curvatures are so small that this principle is often difficult to apply, and to disentangle these effects a statistical study of the differ-

* The 48 in Miss Lehmann's equation at the bottom of p. 255 should be 24.

ences found at twenty-one stations has been made. If the curvatures are due to increase in velocity with depth they will be systematically concave to the distance axis, but those due to other causes will be as often convex as concave. It is therefore possible to say if the velocity increases with depth as a general rule over an area, although there may be some ambiguity at a single station. The differences at these stations range from 3·9 times the standard error in the expected direction to 4·4 times in the opposite direction. The mean is 8×10^{-4} sec., in the expected direction over a range of distance averaging about 3000 ft. The differences are systematically bigger than is to be expected from their standard errors derived from that of a single observation, the sum of the squares of the ratios of the differences to their standard errors being 120 on 20 degrees of freedom. This shows that the curvatures are real. The standard error of the mean estimated from the differences between the stations is 7×10^{-4} sec., and the mean is therefore not significantly different from zero. The same is true if the stations are grouped according to the velocity in the Palaeozoic, and the groups treated separately. None of the rocks forming the floor has therefore, as a general rule, any perceptible increase of velocity with depth. The eight stations (Culford, Bow Brickhill, Fulbourn, Great Staughton, Fenstanton, Lakenheath, Corby and Bourn) at which the difference exceeded twice its standard error were each considered separately, and it was concluded that only at Fenstanton and Fulbourn was there conclusive evidence of an increase of velocity with depth. At these stations the expression (6) was fitted to the residuals by least squares and the constants t_2, v_2 and A and their standard errors determined.

Even when no perceptible curvature is found a slight one may yet be present, and its neglect may cause an error in the calculated depth which is larger than that from all the other causes. To estimate how big this might be we require the standard error of t_2 which would be obtained from fitting the expression (6) to the residuals, but we wish to avoid the considerable labour of actually making a large number of least square reductions. The standard error of t_2 may be shown to be

$$\delta t_2 = \left[\frac{\Sigma x^6 \Sigma x^2 - (\Sigma x^4)^2}{n\{\Sigma x^6 \Sigma x^2 - (\Sigma x^4)^2\} - \Sigma x(\Sigma x \Sigma x^6 - \Sigma x^4 \Sigma x^3) + \Sigma x^3(\Sigma x \Sigma x^4 - \Sigma x^2 \Sigma x^3)}\right]^{\frac{1}{2}} \sigma,$$

where σ is the standard error of a single observation. If the observations are uniformly distributed along a line the summations may be evaluated in terms of the co-ordinates of the beginning and end-points of the line. The expressions thus obtained are inconveniently cumbersome, but simple approximations to them may be obtained by substituting integrals for the summations. The result is

$$\delta t_2 = \frac{4}{(p-1)^2}\left[\frac{4+16p+40p^2+55p^3+40p^4+16p^5+4p^6}{9+17p+9p^2}\right]^{\frac{1}{2}} \frac{\sigma}{\sqrt{n}},$$

where p is the ratio of the greatest to the smallest distance at which the refracted wave is observed. The corresponding result not allowing for curvature is

$$\delta t_2 = \frac{2}{p-1}(1+p+p^2)^{\frac{1}{2}} \frac{\sigma}{\sqrt{n}}.$$

The numerical values are given in table 1; from these it is clear that it is useless to attempt to determine the curvature of the refracted line unless the observed part is at least twice as long as the part to be extrapolated ($p > 3$). If this condition cannot be satisfied it is best to assume the curvature to be zero or known from other lines in the same area.

TABLE 1

	Standard error	
	With curvature	Without curvature
p	$\sigma/\sqrt{n}$	$\sigma/\sqrt{n}$
∞	2·7	2·0
5	5·3	2·8
4	6·4	3·1
3	9·2	3·6
2	20·4	5·3
1·5	56·1	8·7
1	∞	∞

A linear expression (5) has been chosen to fit the variation of velocity with depth because it is the simplest way of approximating to a slight variation. Actually an indefinite number of other expressions could be found giving travel-time curves which fitted the observations as well as (6). It may be shown that if the extrapolated parts of these travel-time curves differ appreciably from (6) the velocity-depth curve must be strongly curved for small depths below the interface. That is, there will only be a large error in the calculated depth due to failure of (5) if the nature of the rock is changing rapidly immediately below the interface. For instance, if the rock immediately below the Palaeozoic floor were changed by the percolation of water from above and elastic waves had a lower velocity in it than in the rock below, the first part of the travel-time curve would be curved and the later part straight; the whole of the curved part might correspond to waves arriving after the direct wave and thus be unobservable. The calculated depth would then be greater than the real depth by an amount of the same order as the thickness of the altered layer. Such effects can only be detected by check measurements at bore-holes and in places where the Palaeozoic is so shallow that only a small part of the refracted line is concealed by the previous arrival of the direct wave. We have found no evidence of such behaviour.

(*c*) *Irregularities in the interface.* These will show up by the mean residuals from a particular shot or a particular geophone being larger than is to be expected from the standard errors of the individual observations. There are a number of cases of this in the present work, but none of them is of any special importance.

(*d*) *Surface irregularities.* The shot points and geophones are not all at the same height. Before fitting straight lines to the observations it is desirable to reduce all the observed times to the values that would have been obtained if they had all been at the mean level of the geophones. If v_1 be the velocity in the material of which the topography is formed, and v_2 that at the lowest point of the ray considered, the correction is

$$\frac{H}{v_1}\left(1-\frac{v_1^2}{v_2^2}\right)^{\frac{1}{2}},$$

where H is the height of the shot-point or geophone above the mean level of the geophones. The correction is never more than a few thousandths of a second, and approximate values of v_1 and v_2 obtained from a graph of the uncorrected observations are sufficient. There is sometimes some doubt as to whether a hill is composed of glacial deposits or of "solid" rock.

(*e*) *Variations of the velocity in the upper layers*. The simple theory assumes that the rocks above the Palaeozoic floor consist of homogeneous layers with velocity increasing downwards, and that the refracted waves through all these layers can be observed. In nature the increase of velocity with depth may occur gradually and not in a series of steps, the time-distance curve will then consist of a curve instead of a series of straight lines. It frequently happens that a set of observations may be fitted equally well by a pair of lines or by a curve; this ambiguity has two consequences: first, we cannot say if the rocks above the Palaeozoic floor consist of two definite layers with a sharp separation, or whether they change continuously with depth; secondly, if we make the wrong choice we shall get an incorrect value for the depth of the Palaeozoic floor. The first of these questions is not of primary importance in the present work, but the second requires detailed consideration. Miss Lehmann (1937) has taken three assumed structures, calculated the time-distance curves, and considered what errors would be made if these curves were approximated to by straight lines. In the first of Miss Lehmann's examples there are three layers, in each of which the velocity increases gradually, and at the interfaces between which there is a sudden jump in velocity. All three parts of the curve are observable as first arrivals and the errors in the depths calculated by assuming the time-distance curves to be straight lines are 2 and 4 %. This example is probably fairly representative of the conditions usually encountered in nature. In her second example the thicknesses of the layers are as before but there is no discontinuity in velocity at either interface, and the depths are 47 and 11 % in error. This shows that the depths of interfaces at which only the rate of change of velocity is discontinuous cannot be determined from the theory for ordinary discontinuities. It also shows that great care should be exercised in cases where it is not known beforehand that a discontinuity in velocity exists. In Miss Lehmann's third example there are two layers of increasing velocity with no discontinuity in velocity between them, and a third layer below them with a discontinuity at its top surface. The wave from the second layer never arrives first, and Miss Lehmann assumes that it would not be observed. The calculated depth of the bottom discontinuity is 16 % in error; in practice the wave from the second layer would probably be observed as a second arrival and the error in depth halved. The large error is not primarily due to the substitution of straight for curved time-distance curves but to the masking of a branch of the curve. For certain of our stations we have made alternative solutions with straight lines and with cube terms fitted to the direct wave time-distance curves. The differences in the depth found for the Palaeozoic floor are comparatively trivial. Since the straight lines correspond to a discontinuous change in velocity at a certain depth and the cube terms to a linear variation, the difference in the results represents the extreme difference that can occur due to the substitution of straight lines for curved time-distance curves. As the cube terms are usually a worse fit than the straight lines the latter have been adopted.

The velocity does not always increase downwards; for example, we may have limestone with a velocity of 12,000 ft./sec. near the surface underlain by clay of velocity 6000 ft./sec.; the wave through the clay can then never arrive before that through the limestone and may not be observable. If we calculate the depth to the Palaeozoic on the information given by the seismic records alone we shall get a result which is twice too big. This gross error may be avoided in two ways: first, if the limestone is a thin band, the wave through it will die out in a few thousand feet; secondly, a study of the surface geology or bore-hole records combined with determinations of velocity at outcrops will indicate in a general way the velocity-depth relation at the place where the measurements are made. This uncertainty in the vertical velocity distribution above the discontinuity whose depth is sought is the principal source of inaccuracy in the seismic method; its effects can best be minimized by a careful correlation of the known geology and the velocities determined over a considerable area. A single station observed in unknown country may be very greatly in error from this cause.

The wave that has travelled through the upper layers can usually be observed even when it arrives after the refracted wave through the Palaeozoic; its time-distance curve is very helpful, as discontinuities in it show changes in velocity with depth which must be allowed for.

5. Distribution of residuals

In the above we have used the ordinary theory of errors based on the normal law. It is therefore desirable to enquire how far the normal law is adequate to describe the distribution of the residuals. The differences between the observed and calculated arrival times for the records at sixteen stations were therefore summarized, those from waves through the Palaeozoic being treated separately from those through the Mesozoic.* The results are given in table 2, where the first column in each section gives the observed number of residuals in 0·001 sec. ranges, the second column gives the number calculated from a normal law with the same total number of observations, N, and the

* For those stations where the time-distance curves contain a cube term, the residuals are those from the adopted curve and not those from the best straight line. It is desirable to treat the waves through the Palaeozoic separately from those through the Mesozoic, as the former are small amplitude refracted waves usually with gradual beginnings, whilst the latter are usually sharp waves of large amplitude but are sometimes not the first waves to arrive.

same standard error, σ. Column 3 gives the differences between the observed and calculated numbers; column 4 gives the square root of the calculated number, being the standard error of the quantities in column 3. Column 5 gives the square of the ratio of the figures in columns 3 and 4. None of the values in the last column would, by itself, be convincing evidence of a departure from the normal law, but their sum (Pearson's χ^2) is much larger than would be expected on the hypothesis that the differences between the observed distribution and the normal law are due to chance. This sum has an expectation equal to the number of groups less the number of parameters determined. Here the latter is one, namely the standard error of one observation, and in this case, therefore, the expectation is 8. The values found were 25·0 for the Palaeozoic, and 18·8 for the Mesozoic. The chances of values greater than these occurring by chance, as given by R. A. Fisher (1936, table 3), are less than 1 in 100 and 1 in 60. The residuals are therefore certainly not a sample from a normal distribution. Since the normal law does not hold the observations should be weighted before fitting straight lines to them, the weights being a function of the residuals from a preliminary solution. This method has been used by Jeffreys (1936) in his investigation of the travel time curves of the waves from earthquakes where the departure from the normal law is much more marked than here, and by Hulme and Symms (1939) in an investigation of the variation of latitude. Such a procedure would considerably increase the work, and we did not consider that the improvement in the results would have justified it.

TABLE 2. DISTRIBUTION OF RESIDUALS

	Palaeozoic					Mesozoic				
	1	2	3	4	5	1	2	3	4	5
Range 10^{-3} sec.	Obs.	Calc.	Obs. −calc.	√calc.	χ^2	Obs.	Calc.	Obs. −calc.	√calc.	χ^2
0·0–0·9	87	72	+15	8·5	3·1	77	72	+ 5	8·5	0·3
1·0–1·9	69	65	+ 4	8·1	0·2	74	67	+ 7	8·2	0·7
2·0–2·9	46	52	− 6	7·2	0·7	73	58	+15	7·6	3·9
3·0–3·9	34	37	− 3	6·1	0·2	32	46	−14	6·8	4·2
4·0–4·9	13	24	−11	4·9	5·0	25	34	− 9	5·8	2·4
5·0–5·9	8	14	− 6	3·7	2·6	17	23	− 6	4·8	1·6
6·0–6·9	3	7	− 4	2·6	2·4	7	14	− 7	3·7	3·6
7·0–7·9	6	3·1	+ 2·9	1·8	2·6	10	8·2	+ 1·8	2·9	0·4
>7·9	6	2·0	+ 4·0	1·4	8·2	12	8·2	+ 3·8	2·9	1·7
	272				25·0	327				18·8

The standard error of a single observation derived from the material in table 2 is $3{\cdot}2 \times 10^{-3}$ sec. for waves through the Palaeozoic, and $4{\cdot}0 \times 10^{-3}$ sec. for waves through the Mesozoic. In the calculation of the standard errors of the velocities and intercepts, it is assumed that the errors at the different distances are independent. It might be supposed that a substantial part of the error would be common to all the observations of a single shot. To investigate the extent to which this is so the mean residual for each shot was subtracted from the residuals used in constructing the part of table 2 referring to the

Palaeozoic, and the standard error recomputed allowing for the reduced number of degrees of freedom. The result was $3\cdot0\times10^{-3}$ sec. in place of $3\cdot2\times10^{-3}$ sec.; the difference is not significant. The errors are therefore sufficiently independent for the uncertainties in the depths and velocities to be calculated in the usual way.

The errors are due to various causes; first, since the movement does not begin perfectly sharply, there is some ambiguity as to where to make the measurement; secondly, the motor does not run quite evenly between successive time marks; and thirdly, any local inhomogeneities in the rocks will cause irregularities in the times. The first of these may be estimated by remeasuring typical records. The result of fifteen pairs of measurements was that this source of error contributed $1\cdot5\times10^{-3}$ sec. to the standard error for the waves through the Palaeozoic. Of this $0\cdot6\times10^{-3}$ sec. was a systematic difference between the observers and $1\cdot4\times10^{-3}$ sec. was random. The former does not contribute to the errors in table 2. The effect of unevenness of the speed of the motor was investigated by estimating the apparent lengths of a number of intervals from 0·01 to 0·6 sec. supplied by a 100 cycle tuning fork. The results showed that this cause contributed $0\cdot7\times10^{-3}$ sec. to the standard error when the 1/10 sec. vibrator was used; with the 1/100 sec. time marks the error will be negligible. The combined effect of these two sources of error is $1\cdot5\times10^{-3}$ sec., leaving $2\cdot8\times10^{-3}$ sec. for the geological irregularities. This is the time taken for a wave to travel 17 ft. with a velocity of 6000 ft./sec. and, as the paths concerned are up to 8000 ft. long, is a very reasonable value. The observed residuals can therefore be accounted for by the known sources of error. At Leighton the shot at 2000 ft. was repeated and seven points on the two records measured independently. The mean difference, taking account of sign, was $0\cdot1\times10^{-3}$ sec., and the square root of the sum of the squares of the differences was $1\cdot3\times10^{-3}$ sec. Since the geological irregularities are the same for both records, this gives an independent estimate of the errors from instrumental causes and from difficulties in reading the records.

The error due to the uneven motion of the motor can easily be reduced by providing a finer time scale. That due to the gradual beginnings could be reduced by using more explosive or, when the steadiness of the ground permits, a higher magnification; if this were done the later phases would be masked by the excessive amplitudes, and it would be necessary to take two records from each geophone, one at a high magnification and one at a low one.

6. Other pulses

In addition to the waves discussed above we have occasionally observed certain other pulses. Some of the near records show waves reflected at the Palaeozoic floor, but they arrive so soon after the direct waves that they are confused with it and their arrival times cannot be determined with sufficient accuracy to be of much use.

Occasionally one or more pulses arrive between the direct and refracted wave whose time-distance curves are straight lines parallel to that of the refracted wave and separated from it by an interval equal to the intercept of the latter on the time axis. Ewing

(1937, p. 769) has previously observed such pulses and has ascribed them to repeated reflexions of the refracted wave at the outer surface and at the interface. We have one station (Fenstanton) where these waves are exceptionally sharp, and a detailed comparison with theory is possible. Many records show rather indefinite pulses at about the time at which these waves would be expected to arrive, but they are usually not definite enough to be measured accurately. They often constitute practically the only motion between the refracted and direct waves.

Nearly every record shows waves with a period of about 0·1 sec. and a velocity of about 1000 ft./sec.; these are presumably surface waves, but we have made no detailed study of them.

We have observed no pulses which could be ascribed to transverse waves. This is in accordance with theory, for an explosion in an infinite homogeneous medium would produce only compressional waves. If there is a free surface and the initial disturbance is a vertical blow on it, distortional waves will also be produced; but Lamb (1904) has shown that such an impulse produces a distortional wave that has only about half of the amplitude of the compressional wave, this would be obscured by the disturbance following the arrival of the compressional wave. With a charge buried at a finite depth the effects will presumably be intermediate between those for the infinite and semi-infinite media. In a quarry blast the conditions are somewhat different, and approximate to an impulsive tangential force on the ground. This might be expected to produce a large distortional wave, and in fact transverse waves are usually observed from such blasts (Leet 1938, chap. 7).

7. Amplitudes

A quantitative study of the amplitudes of the waves is a matter of some difficulty, for the recorded amplitude depends on (*a*) the distance of the shot from the geophone, (*b*) the amount of explosive, (*c*) the depth of the hole in which it is buried, (*d*) the amount of tamping employed, (*e*) the sensitivity of the instrument and its variation with frequency, (*f*) the way in which the geophones are buried, as well as on geological factors. No attempt has been made to disentangle the effect of all these variables, but certain qualitative considerations are useful in the interpretation of the records. First, in clay the amplitude of the direct wave decreases much less rapidly with distance than in chalk. Thus, with clay overlying the Palaeozoic it is usually possible to follow the direct wave to the greatest distances that have been used, its onset is quite sharp and its amplitude is from 3 to 10 times that of the refracted wave. In chalk the attenuation is so rapid that it cannot be followed much beyond the intersection of the direct and refracted time curves, and the refracted wave can occasionally be read before it has overtaken the direct wave (see Swaffham Prior, figure 7); this is never possible with the direct wave in clay. The more rapid attenuation in chalk is presumably due to scattering by the numerous cracks and fault planes by which it is intersected. It is important to observe the direct wave after it is overtaken by the refracted wave, because if it is observed the change of velocity producing the refracted wave must be rapid or discontinuous (the exact conditions have been discussed by Slichter (1932) and special cases by Miss Lehmann (1937)). The gradual increase of velocity with depth such as often occurs in sedimentary deposits produces a change in slope of the time-distance curve, but there is no continuation of the direct wave beyond the bend. Some caution may be necessary in special cases, but in general if the refracted wave is first observed as a small pulse preceding a direct wave of greater amplitude there is a true discontinuity present, whilst if the amplitude of the first arrivals does not change much on going round the bend in the time-distance curve there is no discontinuity.

If the refracted wave is derived from a thick layer it can be followed indefinitely, but if it comes from a thin band such as the Great Oolite Limestone it soon fades out. For example, at Houghton Conquest, where bore-holes show there to be about 25 ft. of limestone,* the refracted wave was observed up to 1600 ft. Increasing the charge does not greatly increase the distance at which the refracted wave from a thin layer can be observed, as the fall in amplitude is very rapid near the limit of observation.

8. Sources of error

The depth of the Palaeozoic floor calculated by the methods set out above may be in error from three causes:

(1) Uncertainties in the determination of the intercepts of the time-distance curves on the time axis;

(2) Uncertainties in the velocities of the waves;

(3) Errors in the correlation of the discontinuities found in the seismic work with the geology.

In principle the first two can be treated by taking the standard errors from the least square solutions and substituting them in the appropriate expression derived by differentiating (2), but owing to the errors of the variables not being independent, the resulting expressions are so cumbersome as to be useless. Fortunately a close approximation may be obtained from elementary considerations. It may be shown that for the velocity ratios ordinarily found between the Palaeozoic and Mesozoic rocks the effect of errors in the velocities on terms of the form $\sqrt{(1-v^2/v_n^2)}$ is small. This means that for the purpose of calculating the uncertainty in the depth of the Palaeozoic floor we may treat the waves as travelling straight down and up at the ends of the refracted path. The uncertainty in the velocity in the Palaeozoic is then only important for its effect on the uncertainty in the intercept, which is calculated in the course of the least square reductions. This error in the intercept will to a first approximation cause an equal proportional error in the depth.

* There is no bore actually at Houghton Conquest, but bores at Bedford and Northill give 20–30 ft. of limestone.

If the velocity v through a depth H has an error δv, the contribution of this to the error in the depth of a deeper layer is, to a sufficient approximation, $H\delta v/v$. If the layer gives an observable branch to the time-distance curve the standard error of the velocity may be calculated from the least squares reductions. If the layer gives no wave (as when it has a lower velocity than the one above it), or if the wave is masked by the previous arrival of other waves, the velocity must be obtained from measurements at other stations or at outcrops. A standard error must then be assigned to it from a consideration of the particular circumstances of each case. If the depth of the interface between layers of velocity v and v' has an error δH, the resulting error in a deeper interface is $\frac{v'-v}{v'}\delta H$. These errors were computed for each station and combined as if they were independent (which, strictly, they are not).

The Palaeozoic is distinguished from the Mesozoic by the difference between their fossil contents, and since seismographs can only find lithological discontinuities, the interpretation of the data in terms of the geological column must involve considerations outside seismology. It involves in fact the following of a lithological feature identified in a bore-hole or at an outcrop into a region in which its depth is not known. This following of a known feature is the crucial point in all applied seismology; the lay-out of the stations and the length of the lines must be chosen so as to reduce the chances of losing the selected horizon and of mistaking another for it. This possibility may be much reduced by arranging the stations in lines, the ends of the lines being at bore-holes. For if an attempt is made to trace the Palaeozoic floor from one bore-hole to another and it is found that a Jurassic limestone is being mapped on arrival at the bore-hole at the other end of the line, a mistake in identification has been made at some point. If such considerations are neglected very serious mistakes may be made, and the structure deduced may bear no relation whatever to nature.

9. Alternative methods of reduction

The methods of reduction described above might be criticized from two points of view. First it might be argued that if the times and distances were plotted on a graph and straight lines drawn through them the results obtained would be practically as good as those got by least squares reduction and much calculation would be avoided. This view (which we held at the beginning of the work) we believe to be unsound and to be one of the causes of the poor results often obtained in refraction shooting. With ordinary draughtsmanship, errors in drawing obscure the departure of the observed points from straight lines and prevent a proper estimate of either the random errors or of systematic curvature. If a real curvature is neglected a large error may be made, whilst if it is decided that a real curvature exists the extrapolation back to the time axis by graphical methods is an extremely arbitrary process. If the person reducing the observations is free to draw lines or curves in any way that looks plausible on a graph it is impossible to avoid bias due to presuppositions as to what the result "ought to be". Further, it is impossible to tell what are the possibilities of random and systematic errors in the results; whether the differences in the results at two stations are to be taken as showing a difference in the depths of the strata or are more probably the result of errors of measurement, or whether the agreement at a bore-hole is satisfactory. As an example of the results of such methods we may quote the controversy as to whether the refracted ray follows the shortest path or goes straight up and down at the ends of its path (a summary and references are given by Haalck 1934, pp. 301–304). The method employed was to make measurements on a discontinuity whose depth was known and to see which theory gave the best results. As curvature of the refracted line and increase in velocity with depth in the upper layers give systematic errors in opposite directions, the result of this test is quite inconclusive without a careful discussion of the systematic errors, for which the residuals from the straight-line solution must be examined. If the residuals from a straight-line solution have to be found there is a great practical convenience in having the residuals from the best straight line. The finding of this best straight line involves little extra work and gives in addition the standard errors of the constants. The advantage of the least squares reductions is not so much that they provide more accurate straight lines as that they provide an objective estimate of the accuracy of the measurements and a method of deciding whether the residuals are random or systematic.

On the other hand, it might be argued that the methods used above do not obtain the maximum of information from the data. It has been shown by Herglotz and Bateman (Jeffreys 1929, pp. 120–123) that if we have a time-distance curve we may obtain the depth-velocity relation by evaluating a certain integral. If there is a rapid increase of velocity with depth the time-distance curve has three branches (the "direct", the "reflected" and the "refracted") and the integral must be taken along all of them, but unfortunately they are usually not all observable. Slichter (1932) has shown that the omission of one of the branches produces an entirely erroneous result. In the above method we have used information about the existence of discontinuities and the occurrence of beds whose velocities are known from measurements made at other stations, to supply the information lost by the failure to observe certain portions of the time-distance curve. This information may most easily be incorporated by treating the rocks as consisting of discrete layers of nearly constant velocity.

10. Example of methods of reduction. Great Staughton

A 6000 ft. line was measured and geophones placed at 0, 200, 400, 600, 800 and 900 ft. and a $\frac{1}{2}$ lb. shot fired at 1000 ft.,* giving times for distances of 100, 200, 400, 600, 800 and 1000 ft. The geophone at 900 ft. was then moved to 1000 ft. and shots fired at 2000 (1 lb.), 3400 ($2\frac{1}{2}$ lb.), 4000 (5 lb.), 5100 (7 lb.) and 6000 ft. (11 lb.). Some of the records are reproduced in figure 3. The observed times for the first arrivals and prominent later

* The sensitivities of the three nearest instruments being suitably reduced.

pulses are given in table 3. The heights of the geophones and shot points above sea-level were:

	Position ft.	Height ft.		Position ft.	Height ft.
Geophones	0	87	Shots	1000	93
	200	87		2000	108
	400	89		3400	105
	600	90		4000	117
	800	91		5100	179
	1000	93		6000	189

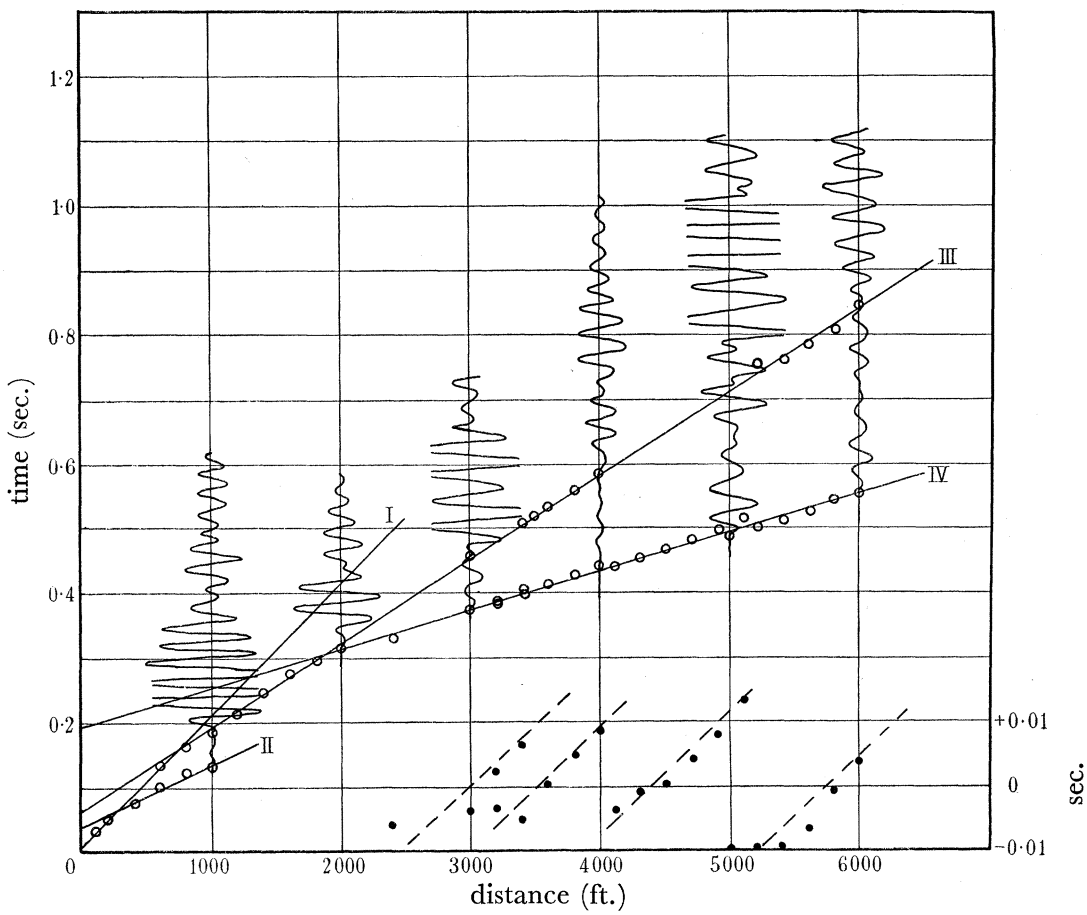


FIGURE 3. Time-distance graph at Great Staughton showing tracings of some records. ○ = observed times (left-hand scale), ● = residuals from least squares straight line IV (right-hand scale), showing the misfit of the records from the different explosions.

Those of the geophones are sufficiently constant to produce no appreciable irregularity in the times, but those of the shot points vary by 96 ft. Corrections to reduce the times to those that would have been obtained if all the shots had been at the mean level of the geophones were applied. The corrected values are given in columns 7–10 of table 3. The biggest correction is 0·0174 sec. (the corrections at this station are the biggest occurring in the work). Columns 11–14 give the differences between the observed times and those calculated from straight-line solutions.

TABLE 3. OBSERVED AND CORRECTED TIMES AT GREAT STAUGHTON

Geophone position ft.	Shot position ft.	Distance ft.	Observed times sec.			Corrected times I	II	III	IV	Obs. − Calc. × 10⁻⁴ sec. I	II	III	IV*
900	1000	100	0·0328	—	—	0·0328	—	—	—	+ 4			
800	1000	200	0·0515	—	—	0·0515	—	—	—	− 5			
600	1000	400	0·0802	—	—	—	0·0797	—	—	—	− 8		
400	1000	600	0·1011	0·1329	0·1583	0·1329	0·1006	0·1583	—	−29	+ 5	+130	
200	1000	800	0·1227	0·1664	0·1822	0·1664	0·1222	0·1822	—	+26	+28	+106	
0	1000	1000	0·1396	0·1922	—	—	0·1391	0·1922	—	—	− 1	−56	
1000	2000	1000	0·1392	0·1880	—	—	0·1361	0·1849	—	—	−31	−29	
800	2000	1200	0·2186	—	—	—	—	0·2155	—	—	—	−86	
600	2000	1400	0·2504	—	—	—	—	0·2473	—	—	—	−31	
400	2000	1600	0·2783	—	—	—	—	0·2752	—	—	—	−15	
200	2000	1800	0·2998	—	—	—	—	0·2967	—	—	—	−62	
0	2000	2000	0·3291	—	—	—	—	0·3260	—	—	—	−32	
1000	3400	2400	0·3394	—	—	—	—	—	0·3368	—	—	—	−56
200	3400	3200	0·3961	—	—	—	—	—	0·3935	—	—	—	+22
0	3400	3400	0·4128	—	—	—	—	—	0·4102	—	—	—	+67
1000	4000	3000	0·3799	0·4709	—	—	—	0·4772	0·3752	—	—	+72	−39
800	4000	3200	0·3929	0·4932	—	—	—	0·4895	0·3882	—	—	+27	−31
600	4000	3400	0·4033	0·5184	—	—	—	0·5147	0·3986	—	—	+16	−49
400	4000	3600	0·4209	0·5431	—	—	—	0·5394	0·4162	—	—	0	+ 5
200	4000	3800	0·4376	0·5730	—	—	—	0·5693	0·4329	—	—	+37	+50
0	4000	4000	0·4537	0·5941	—	—	—	0·5904	0·4490	—	—	−15	+89
1000	5100	4100	0·4585	—	—	—	—	—	0·4430	—	—	—	−33
800	5100	4300	0·4733	—	—	—	—	—	0·4578	—	—	—	− 7
600	5100	4500	0·4866	—	—	—	—	—	0·4711	—	—	—	+ 4
400	5100	4700	0·5031	—	—	—	—	—	0·4876	—	—	—	+47
200	5100	4900	0·5187	—	—	—	—	—	0·5032	—	—	—	+81
0	5100	5100	0·5361	—	—	—	—	—	0·5206	—	—	—	+133
1000	6000	5000	0·5088	0·7469	—	—	—	0·7332	0·4914	—	—	+100	−98
800	6000	5200	0·5213	0·7758	—	—	—	0·7621	0·5039	—	—	+126	−95
600	6000	5400	0·5337	0·7798	—	—	—	0·7661	0·5163	—	—	− 97	−94
400	6000	5600	0·5491	0·8048	—	—	—	0·7911	0·5317	—	—	−110	−62
200	6000	5800	0·5668	0·8284	—	—	—	0·8147	0·5494	—	—	−136	− 7
0	6000	6000	0·5840	0·8681	—	—	—	0·8544	0·5666	—	—	− 2	+43

* These are the residuals from the straight line (7), the residuals after allowing for slope are given in the text.

From a graph of the corrected times (figure 3) it is clear that the first arrivals at 100 and 200 ft. lie on a straight line with the second arrivals at 600 and 800 ft. This straight line cannot be traced further. It is called I in table 3 and figure 3. At about 300 ft. a small high-velocity wave called II in table 3 and figure 3 appears; this can be traced to 1000 ft. where it becomes very faint.

There are only a few points on these lines, and straight lines were fitted by making them pass through the mean of the first and last pairs of points. The results were:

$$t = 0{\cdot}0128 + x/5120 \qquad t = 0{\cdot}0414 + x/10230$$
$$\pm 0{\cdot}004 \quad \pm 150, \qquad \pm 0{\cdot}005 \quad \pm 700.$$

A further high-velocity wave IV in table 3 and figure 3 comes in at about 1800 ft. and arrives first all the way out to 6000 ft. The best straight line through it is

$$t = 0{\cdot}1958 + 0{\cdot}61086 \times 10^{-4} x. \tag{7}$$

A wave with a velocity of 7610 ± 46 ft./sec. (III in table 3, figure 3) is defined by first arrivals from 1200 to 1800 ft. and by second arrivals from there to 6000 ft. The best straight line is

$$t = 0{\cdot}0665 + 1{\cdot}3135 \times 10^{-4} x$$
$$\pm 0{\cdot}0034 \quad \pm 0{\cdot}0080.$$

The residuals are satisfactory considering that the wave is not usually the first to arrive.

As the line I does not go through the origin there is presumably a thin surface layer (of thickness H_1) of velocity less than 5120 which would have been revealed had measurements been taken at distances of less than 100 ft. (as they were at some stations). This layer makes very little difference to the calculated depths of the lower discontinuities and may be roughly allowed for by assuming a segment of the time-distance curve to run from the origin to the first observed point (velocity 3000 ft./sec.). The depth $H_1 + H_2$ of the 10,230 ft./sec. layer may then be found from the following relations:

$$\left.\begin{aligned} 0{\cdot}0128 &= \frac{2H_1}{3000}\left(1 - \frac{3000^2}{5120^2}\right)^{\frac{1}{2}}, \\ 0{\cdot}0414 &= \frac{2H_1}{3000}\left(1 - \frac{3000^2}{10{,}230^2}\right)^{\frac{1}{2}} + \frac{2H_2}{5120^2}\left(1 - \frac{5120^2}{10{,}230^2}\right)^{\frac{1}{2}}. \end{aligned}\right\} \tag{8}$$

This gives

$$\begin{aligned} H_1 &= 24\text{ ft.} \\ H_2 &= 77\text{ ft.} \\ H_1 + H_2 &= 101 \pm 15\text{ ft.} \end{aligned}$$

As the geophones are 89 ft. above sea-level this gives 12 ± 15 ft. below O.D. as the depth of the transition from 5120 to 10,230 ft./sec., bores 1300 and 4400 ft. south-east of the line struck, "rock" at 8 and 12 ft. below sea-level. There is little doubt that the 10,230 ft./sec. branch of the time-distance curve corresponds to this rock. Since the wave cannot be detected at distances greater than 1000 ft. it is probable that the rock is a band of no great thickness and is underlain by rocks having a lower velocity; this is in accordance with the evidence derived from a consideration of a great number of bore-holes (§ 12) which indicates that the Great Oolite Limestone should occur at about this depth. In calculating the depths of the 5120–7610 and 7610–14,600 ft./sec. interfaces we neglect this band. This is equivalent to assuming that a layer which is probably about 10 ft. thick has a velocity of 5120 instead of 10,230 ft./sec., and the error produced is only a few feet.

The observations of the 7610 ft./sec. wave lie on a good straight line which can be traced to the furthest record as a second arrival. The points on the line IV, however, show a marked systematic trend of the kind to be expected from a slope (figure 3). The residuals in 10^{-4} sec. are:

Geophone position	Shot position 3400	4000	5100	6000	Mean	Calc.	Obs. − calc.
1000	−56	−39	−33	−98	−56	−78	+22
800	—	−31	− 7	−95	−44	−49	+ 5
600	—	−49	+ 4	−94	−46	−19	−27
400	—	+ 5	+47	−62	− 3	+10	−13
200	+22	+50	+81	− 7	+36	+39	− 3
0	+67	+89	+133	+43	+83	+69	+14
Mean	—	+ 4	+38	−52			

The means for all the shots lie fairly well on the line

$$-0{\cdot}0078+0{\cdot}1467\times10^{-4}x \pm 0{\cdot}028. \tag{9}$$

The standard error of one observation, calculated from the differences between this expression and the means of the rows, is 0·0034 sec. The residuals are now reduced by the use of (9) to the centre of geophone line, the results are:

TABLE 4

Geophone position	Shot position 3400	4000	5100	6000
1000	+17	+34	+40	−25
800	—	+13	+37	−51
600	—	−35	+17	−80
400	—	−10	+32	−77
200	−22	+ 6	+37	−51
0	− 6	+15	+59	−31
Mean	− 4	+ 4	+37	−52

The best line through the means of the columns is

$$+0{\cdot}0016-0{\cdot}0043\times10^{-4}x;$$

if this is applied as a correction to (7) we have

$$0{\cdot}1974+0{\cdot}6066\times10^{-4}x. \tag{10}$$

The last correction is only worth applying when there is a considerable slope; even then it is necessarily zero unless there are, as here, some missing observations. The true velocity V and the component α of the slope of the interface along the line may be calculated by combining (10) with (7) and (9):

$$V = 2\times 10^4/(0\cdot 6066+0\cdot 7576) = 14{,}660\,\text{ft./sec.}$$

$$\alpha = \frac{7610}{2}\,\frac{(0\cdot 1467+0\cdot 0043)\,10^{-4}}{(1-7610^2/14{,}660^2)^{\frac{1}{2}}} = 0\cdot 068 \text{ radian} = 3\cdot 9^\circ \pm 0\cdot 7.$$

The slope is in such a direction that the geophones are at the deep end; it is the largest slope found in this work. The large means of the last two columns of table 4 are probably due to departures from a uniform slope. As the line has not been shot in both directions the interpretation as a slope is not unambiguous. The results could equally well be explained by a slope twice as great under the geophones and a level Palaeozoic floor under the rest of the line or by a difference in the velocity of elastic waves in the Palaeozoic under the two ends of the line. These uncertainties could be removed by shooting in the reverse direction, but as they do not affect the calculated depth it has not been thought worth while to do so. If the slope were only under the part of the line on which the geophones lie the velocity in the Palaeozoic would be 16,370 ft./sec., and as this velocity is very close to that obtained at the neighbouring station at Pertenhall we have adopted it.

From the line I the velocity above the 10,230 ft./sec. layer is 5120. Lower down the velocity is 7610 (line III), but there is no indication of what the velocity is above this and below the bottom of the 10,230 ft./sec. layer. The rock giving a velocity of 7610 ft./sec. is probably the Lower Lias, and the rock whose velocity is unknown is therefore mostly Upper Lias with some Inferior Oolite; from measurements at the outcrop of the Upper Lias the velocity may be taken as 6800 ft./sec. The thicknesses H_3 and H_4 of the 6800 and 7610 layers are given by

$$0\cdot 0655 = \frac{2H_1}{3000}\left(1-\frac{3000^2}{7610}\right)^{\frac{1}{2}} + \frac{2H_2}{5120}\left(1-\frac{5120^2}{7610^2}\right)^{\frac{1}{2}} + \frac{2H_3}{6800}\left(1-\frac{5120^2}{6800^2}\right)^{\frac{1}{2}},$$

$$0\cdot 1974 = \frac{2H_1}{3000}\left(1-\frac{3000^2}{16{,}370^2}\right)^{\frac{1}{2}} + \frac{2H_2}{5120}\left(1-\frac{5120^2}{16{,}370^2}\right)^{\frac{1}{2}}$$
$$+\frac{2H_3}{6800}\left(1-\frac{6800^2}{16{,}370^2}\right)^{\frac{1}{2}} + \frac{2H_4}{7610}\left(1-\frac{7610^2}{16{,}370^2}\right)^{\frac{1}{2}}.$$

In these expressions the thickness of the 10,230 layer has been neglected. Combining these with (8) gives

H_1	=	24 ft.
H_2	=	77 ,,
H_3	=	223 ,,
H_4	=	437 ,,
		761 ,,
Surface height	=	89 ,,
Top of 16,370 layer		672 ft. below sea-level.

The uncertainty of the total depth depends principally on the uncertainty of the intercept, 0·1974 sec. This cannot be computed directly from the residues in table 4, as these are clearly not independent (e.g. all those from the 5100 ft. shot are positive). In determining the intercept we have extrapolated to zero from observations between 2400–6000 ft., an exact calculation would be troublesome, but from an inspection of table 4 a standard error of 70×10^{-4} seems a liberal estimate. This would contribute 26 ft. to the standard error of the depth. The 7610 velocity has a standard error of 0·6 % which contributes 3 ft. to the uncertainty of the depth, the uncertainty in the 5120 velocity contributes 10 ft. The depth 5120–7610 interface has a standard error of about 12 ft. (depending principally on the uncertainty of the intercept of 5120 ft./sec. line). This contributes 4 ft. to the uncertainty of the depth of the 7610–16,370 ft./sec. discontinuity. There may be thin bands of sand such as the Estuarine beds, or of limestone such as the Marlstone that we have not taken into account; these will have a different velocity from that assumed in the calculation and it is desirable to allow 20 ft. for their effect. The square root of the sum of the squares of these uncertainties is 35 ft. This is taken as the standard error of the depth. If the 6800 ft./sec. layer had been neglected the calculated depth would have been reduced by 38 ft.

For the reasons stated below the 16,370 ft./sec. layer is taken as the Palaeozoic. The 5120 ft./sec. layer is clearly the Oxford Clay, the 7610 ft./sec. comes immediately on the Palaeozoic and must be the Lower Lias. The Great Oolite, Cornbrash and Kelloways Beds constitute the thin band at −12 ft. O.D. The measurements do not indicate the separate layer between the top of the 7610 ft./sec. layer and the bottom of this band, for which we have assumed a velocity of 6800 ft./sec. The 6800–7610 ft./sec. discontinuity is to be regarded rather as something assumed for convenience of calculation than as a real discontinuity; it is likely that there is really a more or less continuous increase in velocity. The section indicated by the seismic work is therefore as shown in figure 4. The positions of some Jurassic horizons derived by interpolation and extrapolation from bore-holes are also indicated.

11. Discussion of individual stations

It is convenient to divide the stations into three groups. First there are those at which the results are similar to those at Great Staughton which have been described in detail above. These stations in order of latitude are:

Leighton	Madingley	Houghton Conquest
Fenstanton	Bourn	Bassingbourn
Pertenhall	Cambridge	Bow Brickhill
Great Staughton	Tempsford	Arlesey.

At all these stations there is a refracted wave from the Great Oolite as well as one from the Palaeozoic.

The second group of stations lies further east on the Chalk outcrop, this group consists of

Bridgham	Kentford	Saffron Walden
Lakenheath	Swaffham Prior	Meesden
Culford	Fulbourn	Westmill.

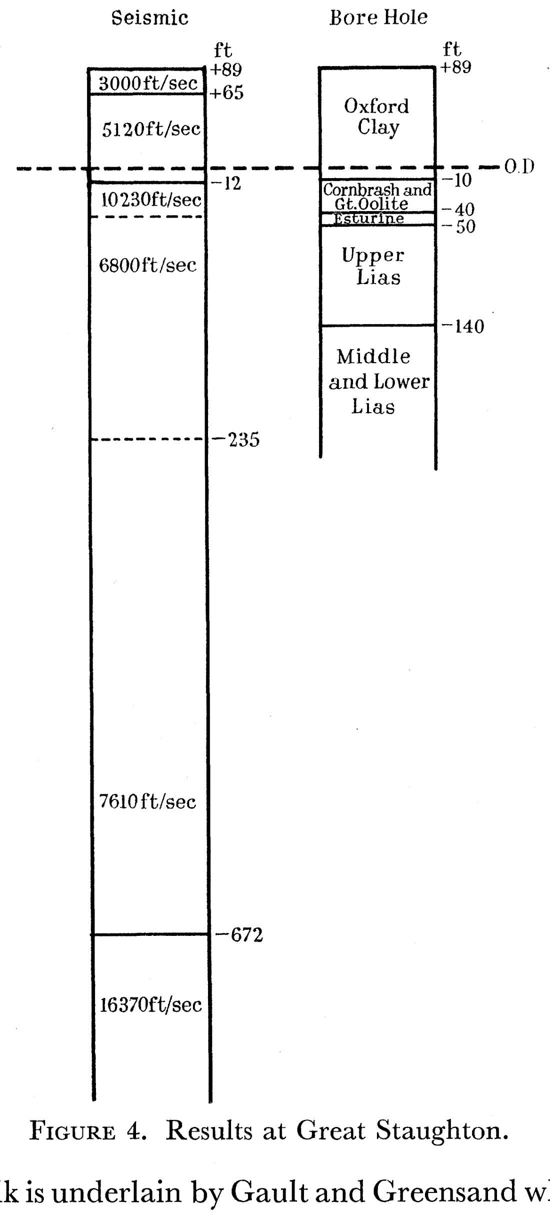


FIGURE 4. Results at Great Staughton.

At all of these the Chalk is underlain by Gault and Greensand which rest directly on the Palaeozoic. The records are very simple, the time curve consisting of three branches, a short one corresponding to waves travelling in a surface layer of sand or boulder clay, one corresponding to waves in the Chalk, and one from the Palaeozoic. The wave in Chalk is rapidly attenuated and is not usually at all clear on the more distant records where it arrives after the direct wave.

The third group consists of stations on the Inferior Oolite or Upper Lias where the Palaeozoic is overlain by Jurassic rocks whose velocity increases downwards. The time-distance curves are similar to those of the first group except that the wave from the Great Oolite is absent. Some of them are complicated by a high velocity layer (probably the Trias) above the Palaeozoic. These stations are

Laxton	Feltwell
Benefield	Great Oxendon.
Corby	

Feltwell is included here and not in the first group as, although it lies on the Oxford Clay, the Great Oolite Limestone is absent.

The results at the individual stations are summarized in table 5. This gives the intercepts and velocities of the various straight-line branches into which the time-distance curve has been analysed together with their standard errors. The thicknesses of the corresponding layers and the geological interpretation of them are also given. It is likely that many of these layers are not sharply bounded; the thicknesses and velocities given then merely indicate the general nature of the variation of velocity with depth and are not to be taken as indications of discontinuities at these depths and at no others (such layers are bracketed together in table 5). The lithological changes in the English Jurassic are so numerous that it is not possible to follow more than the general outline by the refraction method. The discontinuity at the depth interpreted as the Palaeozoic floor is in all cases sharp; this is shown by a sharp break in the time-distance curve and by a continuation of the direct wave beyond the break. The velocities of the various waves and the depths to the Palaeozoic floor and to the Great Oolite are summarized in table 6. The velocities at Great Staughton and Bourn are queried, as these stations showed a slope sufficient to effect the velocities and were only shot in one direction.

We now give short notes on the peculiarities of the individual stations and some typical time-distance curves and reproductions of records. The three groups of stations are dealt with in order, but the individual stations are arranged in the order that is convenient for description.

Pertenhall. This station is only 4 miles from Great Staughton, and the records obtained were so similar that it is not necessary to describe them in detail. The Great Oolite is found to be very near the surface; this would be expected, as the station is only 2 miles from Risley where the Cornbrash is exposed as an inlier in the Oxford Clay.

Bow Brickhill. The time-distance curve consists of three branches. First there is a branch with a velocity of 5000 ft./sec. which is only observed as a first arrival at distances of less than 200 ft., but which is continued by rather indefinite second arrivals to 1000 ft. Next there is a line with a velocity of 11,200 ft./sec. which rapidly fades out and is not observable beyond 2000 ft. Lastly there is a well-marked line observed from 1800 to 5000 ft. with a velocity of 11,260 ft./sec. The interpretation of the records at this and the succeeding four stations might be in doubt if any one of them stood alone, but taken

TABLE 5. RESULTS OF SEISMIC WORK (QUANTITIES ASSUMED FROM MEASUREMENTS MADE AT OTHER STATIONS ARE IN BRACKETS)

No.	Name	Lat.†	Long.†	Ht.† ft.	Az.*	Length of line ft.	Velocity ft./sec.	S.E.‡	Intercept sec.	S.E.‡ × 10⁻⁴	Thickness ft.	Material
1	Laxton	52° 33·0′ N	0° 37·0′ W	340	354°	7600	2,000	400	0·0000	—	43	
							7,380	140	0·0411	19	190	Upper Lias
							8,740	67	0·0690	35	952	Middle and Lower Lias
							10,860	350	0·2094	210	286	Trias?
							17,800	320	0·3210	56	—	Pre-Cambrian
								Total to Pre-Cambrian			1471 ± 50	
								,,			1131	below O.D.
2	Benefield	52° 30·6′ N	0° 32·2′ W	245	269	7400	4,000	—	0·0000	—	32	
							72,50	72	0·0133	12	328	Upper Lias
							8,690	33	0·0660	7	830	Middle and Lower Lias
							18,040	290	0·2656	83	—	Pre-Cambrian
								Total to Pre-Cambrian			1190 ± 50	
								,,			945	below O.D.
3	Corby	52° 30·3′ N	0° 39·4′ W	345	65	8000	3,800	—	0·0000	—	58	
							6,910	64	0·0257	21	217	Upper Lias
							8,650	82	0·0654	32	588	Middle and Lower Lias
							9,590	105	0·1297	69	569	Trias?
							18,670	320	0·3119	59	—	Pre-Cambrian
								Total to Pre-Cambrian			1432 ± 50	
								,,			1087	below O.D.
4	Feltwell	52° 30·0′ N	0° 27·2′ E	0	202	5100	2,000	—	0·0000	—	19	Peat
							5,810	164	0·0182	34	90	Gault
							6,460	225	0·320	87	368	Oxford Clay
							7,210	130	0·0879	86	353	Middle and Lower Lias
							17,540	527	0·2438	59	—	Palaeozoic
								Total to Palaeozoic			830 ± 40	
								,,			830	below O.D.
5	Bridgham	52° 26·4′ N	0° 51·3′ E	126	297	5800	4,000	—	0·0000	—	86	
							7,750	64	0·0366	49	652	Chalk
							(6,000)	500	—	—	(80)	Gault
							19,600	584	0·2197	63	—	Palaeozoic
								Total to Palaeozoic			818 ± 40	
								,,			692	below O.D.

* True bearing of shots from geophones. † Of centre geophone. ‡ S.E. = standard error.

TABLE 5 (*continued*)

No.	Name	Lat.	Long	Ht. ft.	Az.	Length of line ft.	Velocity ft./sec.	S.E.	Intercept sec.	S.E. $\times 10^{-4}$	Thickness ft.	Material
6	Great Oxendon	52° 25·8′ N	0° 56·0′ W	400	48	4000	5,670	—	0·0000	—	104	
							8,100	50	0·0263	14	648	Lower Lias
							16,960	470	0·1752	56	—	Pre-Cambrian
									Total to Pre-Cambrian		752 ± 40	
									,,		352	below O.D.
7	Leighton	52° 22·3′ N	0° 20·7′ W	212	300	6400	1,500	—	0·0000	—	8	
							6,060	54	0·0109	12	179	Oxford Clay
							11,920	144	0·0622	11	—	Great Oolite
							(6,800)	500	—	—	184 }	Upper Lias
							8,330	100	0·0833	34	764 }	Middle and Lower Lias
							15,360	106	0·2703	22	—	Palaeozoic
									Total to Palaeozoic		1135 ± 30	
									,,		923	below O.D.
									Great Oolite		25	above O.D.
8	Lakenheath	52° 23·6′ N	0° 33·4′ E	30	35	6000	7,480	37	0·0037	11	773	Chalk (and Jurassic)
							(6,000)	500	—	—	(70)	Gault
							15,890	418	0·2057	75	—	Palaeozoic
									Total to Palaeozoic		843 ± 40	
									,,		813	below O.D.
9	Culford	52° 18·2′ N	0° 41·6′ E	108	283	5700	1,600	100	0·0000	—	40	Sand and clay
							8,060	120	0·0488	20	540	Chalk
							(6,000)	500	—	—	(70)	Gault
							16,640	230	0·1868	33	—	Palaeozoic
									Total to Palaeozoic		650 ± 30	
									,,		542	below O.D.
10	Fenstanton	52° 17·6′ N	0° 04·8′ W	30	223	6200	3,000	—	0·0000	—	19	
							5,560	72	0·0105	20	136	Oxford Clay
							9,300	1000	0·0512	100	—	Great Oolite
							(8,000)	500	—	—	380	Lower Lias
							11,580*	40	0·1239	9	—	Palaeozoic
									Total to Palaeozoic		535 ± 30	
									,,		505	below O.D.
									Great Oolite		125	below O.D.
11	Kentford	52° 17·2′ N	0° 30·5′ E	100	127	4200	2,000	—	0·0000	—	21	Sand, etc.
							7,690	75	0·0204	15	682	Chalk (and Jurassic)
							(6,000)	500	—	—	(90)	Gault
							16,170	745	0·2002	96	—	Palaeozoic
									Total to Palaeozoic		793 ± 60	
									,,		693	below O.D.

* Increases by [illegible] % for a 1000 ft. increase in depth.

12	Pertenhall	52° 16·7′ N	0° 26·4′ W	130	88°	4100	5,100	—	0·0000	—	32	Oxford Clay
							9,840	137	0·0127	12	—	Great Oolite
							(6,800)	500	—	—	158 }	Upper Lias
							(7,680)	400	0·0300	100	614 }	Middle and Lower Lias
							16,580	169	0·1929	18	—	Palaeozoic
								Total to Palaeozoic			804 ± 60	
									”		674	below O.D.
								Great Oolite			98	above O.D.
13	Great Staughton	52° 16·4′ N	0° 20·6′ W	89	36	6000	3,000	—	0·0000	—	24	
							5,120	150	0·0128	40	77	Oxford Clay
							10,230	700	0·0414	50	—	Great Oolite
							(6,800)	—	—	—	223 }	Upper Lias and Inferior Oolite
							7,610	46	0·0665	34	437 }	Middle and Lower Lias
							16,370	—	0·1958	70	—	Palaeozoic
								Total to Palaeozoic			761 ± 35	
									”		672	below O.D.
								Great Oolite			12	below O.D.
14	Swaffham Prior	52° 14·2′ N	0° 20·2′ E	108	216	6000	4,000	—	0·0000	—	67	
							8,270	180	0·0296	32	440	Chalk (and Jurassic)
							(6,000)	500	—	—	(100)	Gault
							13,720	64	0·1421	14	—	Palaeozoic
								Total to Palaeozoic			607 ± 30	
									”		499	below O.D.
15	Madingley	52° 14·0′ N	0° 03·2′ E	55	44	6000	2,000	—	0·0000	—	27	
							5,760	75	0·0252	19	354	Gault and Oxford Clay
							11,260	106	0·1315	29	—	Great Oolite
							(8,000)	500	—	—	417	Lias
							13,400	194	0·2213	55	—	Palaeozoic
								Total to Palaeozoic			798 ± 50	
									”		743	below O.D.
								Great Oolite			326	below O.D.
16	Bourn	52° 12·4′ N	0° 02·9′ W	210	305	6000	4,000	—	0·0000	—	15	
							5,970	60	0·0055	15	482	Gault and Oxford Clay
							12,460	640	0·1489	93	—	Great Oolite
							(8,000)	500	—	—	272	Lias
							14,420	300	0·1969	77	—	Palaeozoic
								Total to Palaeozoic			769 ± 50	
									”		559	below O.D.
								Great Oolite			287	below O.D.

TABLE 5 (*continued*)

No.	Name	Lat.	Long	Ht. ft.	Az.	Length of line ft.	Velocity ft./sec.	S.E.	Intercept sec.	S.E. $\times 10^{-4}$	Thickness ft.	Material
17	Cambridge	52° 12·2′ N	0° 06·2′ E	40	276	7200	2,000	—	0·0000	—	22	
							5,900	30	0·0210	5	318	Gault and Oxford Clays
							12,940	180	0·1178	28	—	Great Oolite
							(8,000)	500	—	—	56	Lias
							12,190	180	0·1267	66	—	Palaeozoic
									Total to Palaeozoic		396 ± 30	
									,,		356	below O.D.
									Great Oolite		300	below O.D.
18	Fulbourn	52° 09·6′ N	0° 15·0′ E	125	34	7000	5,300	—	0·0000	—	61	
							7,880	80	0·0169	15	446	Chalk (and Jurassic)
							(6,000)	300	—	—	(100)	Gault
							13,260*	250	0·1373	47	—	Palaeozoic
									Total to Palaeozoic		607 ± 30	
									,,		482	below O.D.
19	Tempsford	52° 09·6′ N	0° 15·3′ W	60	20	6000	2,800	150	0·0000	—	34	
							5,780	180	0·0214	38	124	Oxford Clay
							12,820	410	0·0623	25	—	Great Oolite
							(6,800)	—	—	—	232 }	Upper Lias
							8,760	250	0·0987	73	469 }	Middle and Lower Lias
							13,860	240	0·2062	57	—	Palaeozoic
									Total to Palaeozoic		859 ± 40	
									,,		799	below O.D.
									Great Oolite		98	below O.D.
20	Houghton Conquest	52° 04·8′ N	0° 29·0′ W	110	46	4000	1,800	—	0·0000	—	14	
							7,040	220	0·0151	11	50	Oxford Clay
							10,370	370	0·0259	38	—	Great Oolite
							(8,000)	500	—	—	442	Lias
							12,810	170	0·1028	21	—	Palaeozoic
									Total to Palaeozoic		506 ± 40	
									,,		396	below O.D.
									Great Oolite		46	above O.D.
21	Bassingbourn	52° 03·7′ N	0° 04·6′ W	124	72	6000	3,000	—	0·0000	—	24 }	Chalk, Gault,
							6,330	83	0·0143	22	473 }	Oxford Clay
							10,760	500	0·1364	33	—	Great Oolite
							(8,000)	700	—	—	212	Lias
							13,050	133	0·1934	39	—	Palaeozoic
									Total to Palaeozoic		709 ± 30	
									,,		585	below O.D.
									Great Oolite		373	below O.D.

* Increases by 20% for a 1000 ft. increase in depth.

22	Saffron Walden	52° 01·8′ N	0° 14·8′ E	270	34°	6100	3,100	—	0·0000	—	50	Chalk (and Jurassic)
							7,080	36	0·0179	7	504	
							7,940	38	0·0643	33	249	
							(6,000)	400	—	—	(140)	Gault
							13,200	330	0·2156	96	—	Palaeozoic
								Total to Palaeozoic			943 ± 60	
									,,		673	below O.D.
23	Bow Brickhill	52° 00·7′ N	0° 41·6′ W	220	89	5000	5,000	—	0·0000	—	60	Oxford Clay
							11,200	410	0·0200	34	—	Great Oolite (?)
							(8,000)	500	—	—	345	Lias
							11,260	100	0·0821	29	—	Palaeozoic
								Total to Palaeozoic			405 ± 30	
									,,		185	below O.D.
								Great Oolite (?)			160	above O.D.
24	Arlesey	52° 00·6′ N	0° 17·7′ W	155	81	7300	5,640	30	0·0000	—	427	Gault and Oxford Clays
							11,480	70	0·1318	18	—	Great Oolite
							(8,000)	500	—	—	290	Lias
							13,500	240	0·1957	80	—	Palaeozoic
								Total to Palaeozoic			717 ± 50	
									,,		562	below O.D.
								Great Oolite			272	below O.D.
25	Meesden	51° 58·8′ N	0° 05·1′ E	375	282	5000	3,000	—	0·0000	—	58	Chalk
							7,080	60	0·0348	53	90	
							7,460	84	0·0434	150	528	
							(6,000)	400	—	—	(180)	Gault
							13,580	250	0·2255	48	—	Palaeozoic
								Total to Palaeozoic			856 ± 30	
									,,		481	below O.D.
26	Westmill	51° 54·8′ N	0° 01·7′ W	397	294	6000	2,800	—	0·0000	—	102	Chalk (and Jurassic)
							7,540	45	0·0678	65	670	
							(6,000)	400	—	—	(190)	Gault
							13,760	220	0·2712	59	—	Palaeozoic
								Total to Palaeozoic			962 ± 40	
									,,		565	below O.D.

TABLE 6. SUMMARY OF VELOCITIES (IN FT./SEC.) AND DEPTHS (IN FT.)

Station name	Chalk	Gault	Oxford clay	Great Oolite	Upper Lias	Lower Lias	Trias?	Palaeozoic or Pre-Cambrian	Palaeozoic floor below O.D.	Great Oolite above O.D.
Laxton	—	—	—	—	7380	8740	10,860	17,800	1130	
Benefield	—	—	—	—	7250	8690	—	18,040	940	
Corby	—	—	—	—	6910	8650	9,590	18,670	1090	
Feltwell	—	5810	6460	—	—	7210	—	17,540	830	
Bridgham	7750	—	—	—	—	—	—	19,600	690	
Great Oxendon	—	—	—	—	—	8100	—	16,960	350	
Leighton	—	—	6060	11,920	—	8330	—	15,360	920	+ 20
Lakenheath	7480	—	—	—	—	—	—	15,890	810	
Culford	8060	—	—	—	—	—	—	16,640	540	
Fenstanton	—	—	5560	9,300	—	—	—	11,580	500	−120
Kentford	7690	—	—	—	—	—	—	16,170	690	
Pertenhall	—	—	5100	9,840	—	—	—	16,580	670	+100
Great Staughton	—	—	5120	10,230	—	7610	—	16,370?	670	− 10
Swaffham Prior	8270	—	—	—	—	—	—	13,720	500	
Madingley	—	5760	—	11,260	—	—	—	13,400	740	−330
Bourn	—	5970	—	12,460	—	—	—	14,420?	560	−290
Cambridge	—	5900	—	12,940	—	—	—	12,190	360	−300
Fulbourn	7880	—	—	—	—	—	—	13,260	480	
Tempsford	—	—	5780	12,820	—	8760	—	13,860	800	−100
Houghton Conquest	—	—	7040	10,370	—	—	—	12,810	400	+ 50
Bassingbourn	3000 and 6330	—	—	10,760	—	—	—	13,050	590	−370
Saffron Walden	3100, 7080 and 7940	—	—	—	—	—	—	13,200	670	
Bow Brickhill	—	—	5000	11,200	—	—	—	11,260	180	+160
Arlesey	—	5640	—	11,480	—	—	—	13,500	560	−270
Meesden	7080 and 7460	—	—	—	—	—	—	13,580	480	
Westmill	7540	—	—	—	—	—	—	13,760	560	
Brockhall*	—	—	—	—	—	7680				
Castlethorp*	—	—	—	—	6800					

* These stations do not occur in table 5 as only short lines were shot to determine the velocities at the outcrop.

together they show conclusively that the two lines with nearly the same velocity do really correspond to two different layers which at this station happen to have equal velocities within the errors of measurement. The alternative explanation of a fault step in a single layer is excluded by both waves being observed together at distances around 2000 ft., and also by the occurrence of similar curves at other stations which show that this type of time-distance curve is a common feature of the district and not a peculiarity of this particular line. The line from 1800 to 5000 ft. shows a barely significant curvature which has been neglected.

As the second line fades out rapidly we assume it to correspond to a thin layer which the discussion of § 12 identifies with a combination of the Great Oolite, the Cornbrash, and the Kelloways Beds.* On this assumption we have to assign a velocity to the strata between these limestones and the Palaeozoic. These will be mostly Lower Lias (see § 12) for which the velocity may be taken as 8000 ± 700 ft./sec. (see table 6).

At Bletchley $1\frac{1}{2}$ miles to the west of this line a bore-hole penetrated alternate limestones and clays from 104 ft. above O.D. to 118 ft. below. It then passed through alternate layers of clay and of what the borers stated to be granite to 150 ft. below O.D., where the boring stopped in clay. Fragments of the core are preserved in the Sedgwick Museum, and among them are pieces of granite several millimetres across. It has generally been assumed that the bore passed through boulders of granite and would, if continued for a few feet, have entered solid granite. On the other hand, Mr Cameron, of the Geological Survey, who was present when the boring was in progress, states that the granite formed only a small proportion of the material from the lower part of the bore and that the bulk of it was sandstone.† If this is so, there is no evidence for the existence of granite *in situ* near Bletchley. The seismic results show conclusively that there is no granite within 1200 ft. of the surface at Bow Brickhill. The bottom discontinuity is probably the Palaeozoic floor, and the low velocity may mean that the floor is composed of Cambrian shales as at Calvert 15 miles farther west or it might be due to the presence of coal measures.

Tempsford. The time-distance curve is similar to that obtained at Bow Brickhill. The refracted wave from the Great Oolite dies out rapidly and is not detectable at more than 1900 ft. from the shot point. The depth of the Great Oolite is in good agreement with that obtained by extrapolation from other stations and from its height at bore-holes, and at the outcrop. We neglect this band in computing the depths of discontinuities below it.

The Palaeozoic is much deeper at Tempsford than at Bow Brickhill and there is an interval of 1000 ft. in the time-distance curve between the disappearance of the 12,820 ft./sec. wave and the beginning of the 13,860 ft./sec. line. The first arrivals in this interval give a line of velocity 8760 ft./sec. The top of the 8760 layer is below the Great

* We shall refer to this as the Great Oolite, etc.

† The evidence is summarized in the Buckinghamshire Water Supply Memoir (Whitaker 1921, p. 134).

Oolite. It is presumably the Middle and Lower Lias. The layer between it and the Great Oolite will be the Upper Lias, for which we may assume a velocity of 6800 ft./sec. as at the outcrop.

The refracted line corresponding to the Palaeozoic has no significant curvature but a slope of $1 \cdot 7 \pm 0 \cdot 8^\circ$ with geophones at the deep end is suggested by the residuals.

Houghton Conquest. The results are similar to those at Tempsford except that the Palaeozoic is shallower and the Great Oolite deeper, so that the two refracted waves both occur on the records at 1400 and 1600 ft. The direct wave is very poorly developed, probably because of the thinness of the Oxford Clay (50 ft.): the velocity was determined from points between 25 and 500 ft. as 7040 ± 220 ft./sec. Below the Great Oolite a velocity of 8000 ± 700 ft./sec. was assumed from the results at other stations (see table 6).

The residuals showed a systematic trend characteristic of a slight slope. The calculated slope is $1 \cdot 0 \pm 0 \cdot 5^\circ$ and the true velocity is $12{,}810 \pm 170$ ft./sec.

Leighton. The Great Oolite is 190 ft. deep and the Palaeozoic 1090 ft. This great difference in depth causes the two refracted waves to be exceptionally well separated, and allows the direct wave to be observed as a first arrival between 1400 ft., where the refracted wave from the Great Oolite dies out and 3200 ft. where that from the Palaeozoic overtakes it. This allows a good determination of the velocity in the Lower Lias; at most of the other stations in this group this velocity had to be assumed from that at stations nearer the outcrop. In order to see if the distance at which the refracted wave was observable depended at all critically on the amount of explosive used, the shot at 2000 ft. was repeated with $3\frac{3}{4}$ lb. of gelignite instead of $1\frac{1}{2}$ lb. The wave still died out at about 1400 ft., showing that the decrease of amplitude with distance in a thin layer is very rapid.

Fenstanton. The refracted wave from the Great Oolite limestone was very feeble and was only observed up to 1300 ft. The refracted wave from the Palaeozoic was observed over an exceptionally large range of distances (1300–6000 ft.), and a slight curvature was found and allowed for. The time-distance curve is shown in figure 5. The records at this station at distances greater than 3800 ft. show clear pulses arriving after the refracted wave and before the direct wave. These lie on a line parallel to the refracted line and are probably produced by a wave whose path is similar to the refracted wave except that it has been reflected at the outer surface at some point in its path. The mean of the eight observed points lies $0 \cdot 1334 \pm 0 \cdot 0026$ sec. above the ordinary refracted line. A detailed comparison with theory is complicated by the curvature of the time-distance curve, but it may be shown that the mean separation between this wave and the ordinary refracted wave should be $0 \cdot 1356$ sec. The difference between the observed and calculated differences is so small as to leave little doubt as to the correctness of the identification. Pulses with delays twice and three times this value were also observed on the records at 5800 and 6200 ft.

Bourn. This and the four following stations (Cambridge, Madingley, Bassingbourn and Arlesey) have given great difficulty in interpretation. The direct wave, and a refracted wave at distances between 3000 and 6000 ft. with a velocity of 14,420 ft./sec. are well observed. The distribution of the points about the refracted time-distance line indicates a slope of 2·4° downwards towards the north-west and considerable irregularity in the floor. If this were all, the interpretation would be simple. From 1800 to 3000 ft., however, a refracted wave with a velocity of 12,500 ± 640 ft./sec. is observed. It is probable that this line is to be correlated with the similar lines that have been observed

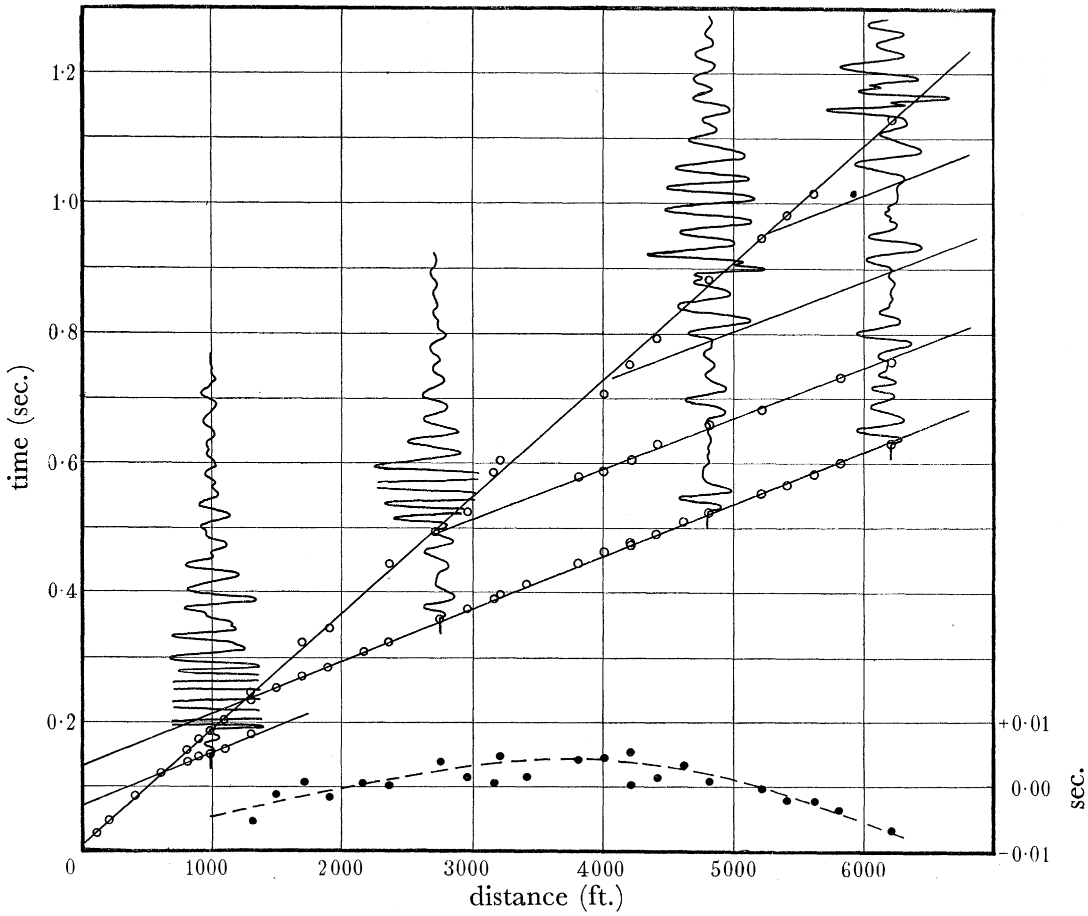


FIGURE 5. Time-distance graph at Fenstanton showing tracings of some records. ○ = observed times (left-hand scale), ● = residuals from least squares straight line (right-hand scale). A slight curvature of the time-distance line for the refracted wave is apparent from the residuals.

farther to the west and that it comes from the Great Oolite. The depths deduced agree well with those extrapolated from bore-holes nearer the outcrop (see figure 8). Against this view it may be objected that at Fenstanton, 6 miles to the north-north-west, the corresponding wave was not observable beyond 1300 ft., and that there must therefore have been a substantial thickening of the limestone layer between the two stations, in contradiction to the general trend of the Jurassic lithology in East Anglia which shows an increasing proportion of clay and shale as we recede from the outcrop. It is of course possible that this tendency is reversed on approaching the eastern shore-line, but it is also possible that limestones may be developed at some other horizon and that the layer at Bourn and the other similar stations is not to be correlated with that at the stations to the west.

[*Note added* 22 November 1939.] Since this paper was written measurements have been made at Calvert in Buckinghamshire. At this station a time distance curve similar to those found at Bourn, Cambridge, etc. was obtained. The calculated depths of the Great Oolite and of the Palaeozoic were 110 and 450 ft. As the surface height was 290 ft. these correspond to 180 ft. above and 160 ft. below sea-level. These results may be compared with those found in the Steeple Claydon and Charndon bores which give 193 and 190 above sea-level for the base of the Oxford Clay and 158 and 153 ft. below sea-level for the Palaeozoic. The good agreement with the bore holes makes it more likely that the interpretation at Bourn and the other similar stations is correct.

Cambridge. The results are similar to those at Bourn except that the wave doubtfully regarded as from the Great Oolite is observable over an even bigger range of distance, and the course of its fading out is more clearly seen. On the records between 2600 and 4000 ft. both it and the refracted wave from the Palaeozoic can be seen. The records at 4400–5400 ft. have been reproduced by Miss Lehmann (1937).

Madingley. It was thought possible that the 12,700 ft./sec. refracted wave at Cambridge might be due to a thick development of Corallian limestones as at Upware. In order to test this hypothesis observations were made at Madingley which is about halfway between Cambridge and the outcrop of the Corallian at Elsworth. The records were very similar to those obtained at Cambridge and the depths are not greatly different. It is therefore unlikely that the layer at 320 ft. at Cambridge and Madingley can emerge as the Elsworth rock a few miles to the west, and it is much more likely that it is to be correlated with the very similar wave at Bourn and hence probably with the Great Oolite.

Bassingbourn. There is some difficulty about the interpretation of the records at this station, as the observations of the refracted wave from 2000 to 3200 ft. do not lie on the same line as those from there to 6000 ft. This is hardly noticeable in a graph of the observed times but is quite clear when the residuals from a straight line are plotted (see figure 6). There are three possible interpretations of this. First, that it is the effect of a continuous increase in velocity with depth in the Palaeozoic. This seems unlikely, as the increase is much larger than that found at any other station (10,800 ft./sec. at distances from 2000 to 3000 ft., and 13,050 ft./sec. from 3600 to 6000 ft.). Secondly, there may be a 10,800 ft./sec. layer lying on one 13,050 ft./sec. Thirdly, there may be a layer of rock giving 10,800 ft./sec. at 373 ft. below O.D. underlain by a low-velocity layer which rests on the Palaeozoic. If the velocity below this layer were 8000 ft./sec. the top of the rock giving 13,050 ft./sec. would lie 709 ft. below the surface. The time-distance plot is very similar to those at Cambridge, Madingley and Bourn, except that the two refracted branches cross before the lower one dies out. We therefore accept the same interpretation, and regard the 10,800 ft./sec. as the Great Oolite, suppose it to be underlain by clays, and adopt 709 ft. for the depth of the Palaeozoic. The reflected-refracted wave referred to in § 6 is observed between 5000 and 6000 ft. (see figure 6).

Arlesey. The results at this station were similar to those at Bassingbourn but with the break in the refracted branch of the time-distance curve at 5300 ft. instead of 3300 ft. It is not possible to feel much confidence in the interpretation of the results at these two stations. The existence of the discontinuity at 272 ft. is not in doubt, and the depth deduced for it fits well with that expected for the Great Oolite whilst it is improbably shallow for the Palaeozoic floor. We have therefore treated the somewhat dubious lower discontinuity as representing the Palaeozoic floor.

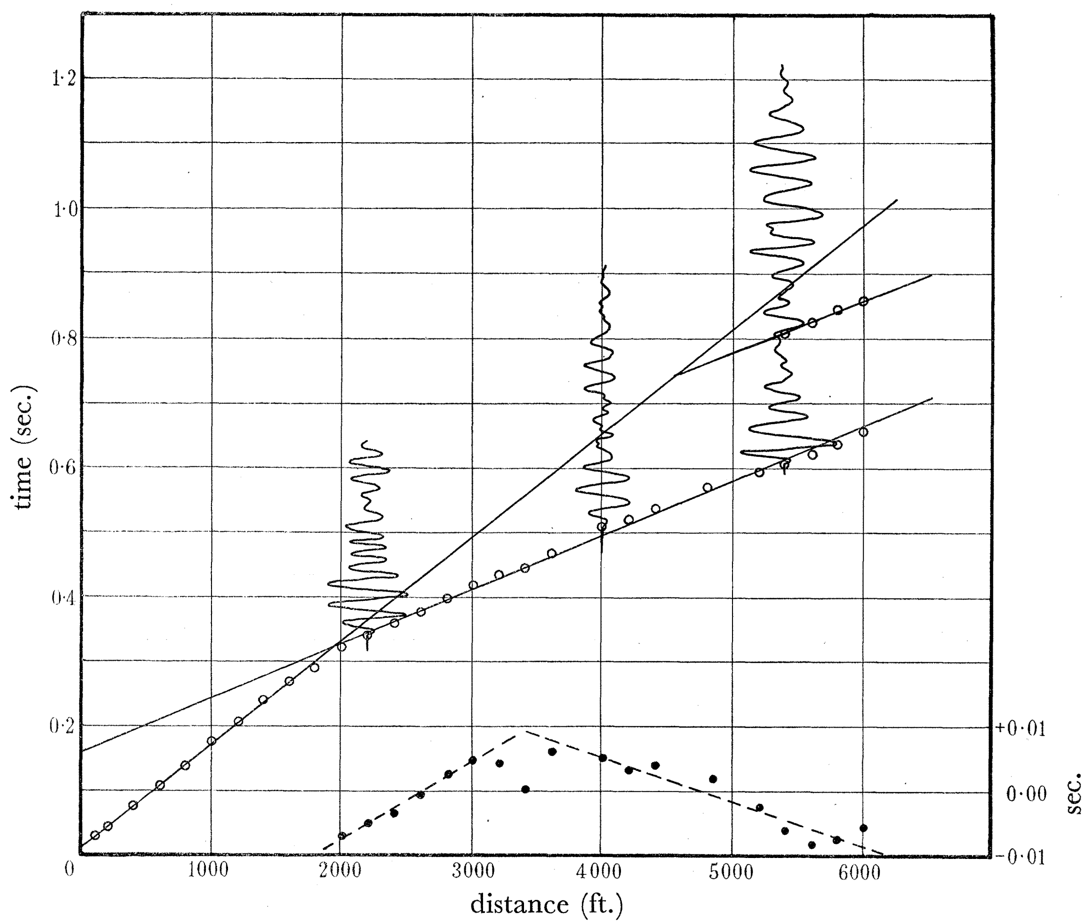


FIGURE 6. Time-distance graph at Bassingbourn showing tracings of some records. ○ = observed times (left-hand scale), ● = residuals from least squares straight line (right-hand scale).

Culford. The time-distance curve consisted of three parts, corresponding to a surface layer of sand and boulder clay, to the Chalk, and to the Palaeozoic. The calculated depth is 650 ± 25 ft. (540 below sea-level). A bore-hole $\frac{1}{4}$ mile from the line reached the Palaeozoic at 637 ft. (527 below O.D.). The velocity in the Chalk was 8060 ft./sec., which is unusually high. At this and the succeeding eight stations an allowance has been made for the Gault below the Chalk. A velocity of 6000 ft./sec. has been assumed and the thickness taken from Morton's (1928) map. The correction is 20 ft. at Culford. It is not possible to make a similar correction for the Greensand as its thickness is variable and the velocity in it has not been measured.

Kentford. The results were similar to those at Culford except that circumstances did not allow a line more than 4300 ft. long to be shot and the depth has therefore a relatively large uncertainty.

Swaffham Prior. The results were similar to those at Culford and Kentford except that the direct wave dies out so rapidly that the refracted wave can be discerned before it overtakes the direct. This very rarely happens. The time-distance curve and some tracings of records are shown in figure 7. There are observations of the refracted wave from 1000

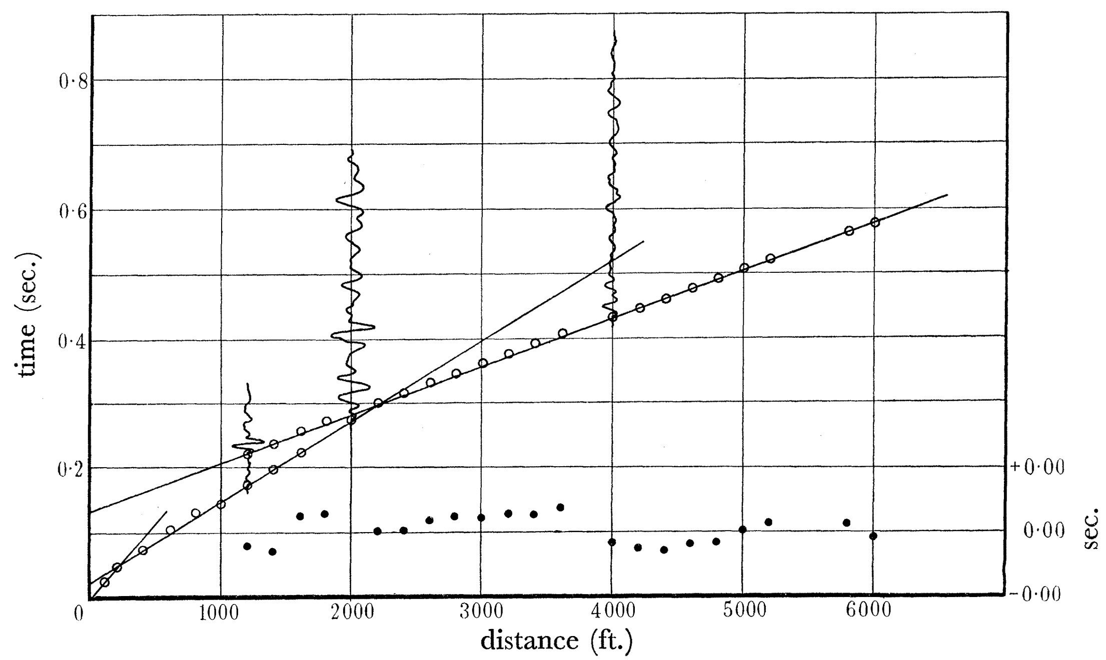


FIGURE 7. Time-distance graph at Swaffham Prior showing tracings of some records. ○ = observed times (left-hand scale), ● = residuals from least squares straight line (right-hand scale).

to 6000 ft.; they show no trace of curvature. At this and at some of the other stations in this group a consideration of the bore-hole data (figure 13) shows that the Greensand can not rest directly on the Palaeozoic floor. The velocity in the rocks below (Oxford or Kimeridge Clay and Lias) will not differ greatly from that in the Chalk and it is not necessary to consider them separately.

Fulbourn. The results were similar to the above except that the velocity in the Chalk near the surface is less than that deeper down; for purposes of calculation a homogeneous layer with a low velocity has been assumed though the transition may well be continuous. The refracted wave is observed from 2400 to 7000 ft. and shows a well-marked curvature which has been allowed for in finding the depth. One of the records is reproduced in figure 19, plate 6.

Lakenheath. This line was shot on heath land underlain by 10–20 ft. of sand. Variations in the thickness of this sand could cause considerable variations in the time of travel of the waves, and it was therefore determined under each geophone and shot point by the methods described in § 4*a*. Apart from the wave through the sand only two waves were observed, that through the Chalk, and that from the Palaeozoic.

Bridgham. The results were similar to those at Culford except that the velocity in the Palaeozoic is much higher and suggests an igneous rock. One of the records is reproduced in figure 21, plate 7.

Meesden. Similar to Culford.

Westmill. Similar to Culford. One of the records is reproduced in figure 20, plate 6.

Saffron Walden. Similar to Culford but with a 4° slope in the Palaeozoic floor, downwards towards the south-west. A bore-hole made near this town in 1836 is said to have been carried to 1013 ft. below the surface without reaching the Palaeozoic floor. There are great difficulties in interpreting the record (H. J. Osborne White 1932) and we do not consider that any useful information can be derived from it. In view of the possibility of the bore having deviated considerably from the vertical and to the doubt about the surface height, it is not inconsistent with our result of 943 ± 60 ft. below the surface.

Corby. An 8000 ft. line was shot in both directions at this station. The results for the two directions do not differ appreciably and have been combined. There is a very clear refracted wave with velocity 18,670 ft./sec. observed from 4000 to 8000 ft. and showing no curvature. The direct wave has been somewhat arbitrarily divided into four branches with velocities 3800, 6910, 8650 and 9590 ft./sec. It is not possible to say with certainty whether the transition between the layers with these velocities is sharp or continuous. For convenience of computation the depth of the Palaeozoic has been computed as if they were sharply defined layers. The 6910 velocity is presumably that in the Upper Lias, and the 8650 that in the Lower Lias. The 9590 layer suggests the presence of Trias; this is also required from a consideration of the thicknesses of the Lias derived from bore-holes. One of the records is reproduced in figure 18, plate 6.

Benefield. The results were similar to those at Corby. The line was shot in both directions, the difference between the results indicated a slope of $1{\cdot}4 \pm 0{\cdot}5°$ dipping towards the west. The 9590 ft./sec. layer found at Corby was not observed at Benefield; this is consistent with its being the Trias (see section C, figure 15).

Laxton. The results were similar to those at Corby and Benefield. A layer with a velocity of $10{,}860 \pm 320$ ft./sec. was found above the Palaeozoic, and is presumably the same as the 9590 ft./sec. layer at Corby.

Great Oxendon. This line was shot near a bore-hole which penetrated 678 ft. of Lias, 18 ft. of Rhaetic and 64 ft. of Trias, and at 760 ft. entered a felsite similar to that exposed at Charnwood Forest. The depth found from the seismic work was 817 ± 30 ft. The velocity in the rocks above the felsite increased with depth; it is not certain if the transitions are sharp or continuous. The velocity in the felsite was found to be 16,970 ± 470 ft./sec.

Feltwell. The results were similar to those at Benefield.

12. Contours of the Jurassic and Cretaceous

A knowledge of the depths and thicknesses of the Jurassic and Cretaceous rocks is required for two purposes in the interpretation of the seismic work. First, some of the stations show two discontinuities, and it is necessary to decide whether the upper of these is the Palaeozoic floor or a Jurassic limestone, and secondly, it is often necessary to infer the velocity of elastic waves for part of their path from velocity measurements at other stations, and for this to be done successfully we must know what kind of rock is to be expected at various depths above the Palaeozoic floor. The statements in text-books and papers are usually vague and qualitative, and it seems that no systematic attempt has hitherto been made to collect all the data bearing on the structure of the area.

The data consist of the outcrops marked on the Old and New Series 1 in. to a mile maps of the Geological Survey,* and the bore-hole sections and comments thereon published in the County Water Supply Memoirs and preserved in the files of the Geological Survey. The bore-hole sections are usually those prepared by the workmen who made the boring and are often vague and unsatisfactory; it is therefore necessary to choose horizons marked by an easily identifiable change in lithology. The base of the Cornbrash and of the Great Oolite Limestone were chosen for detailed examination. Tracings of the outcrops were made on a scale of 1 in. to a mile (1 : 63,360), superposed on topographic maps on the same scale (the "Popular" edition), and the points where the contours cut the outcrops were noted. In this way the heights of about 1000 points were determined. Next, all the published bore-hole data were abstracted, the sites of the bores identified where possible on the 6 in. to a mile (1 : 10,560) maps, and the surface heights estimated where they were not already known. Application was then made to the Geological Survey for unpublished information. A list was prepared† of all the bores more than 100 ft. deep on new series sheets Nos. 144, 145, 157, 158, 159, 171, 172, 173, 185, 186, 187, 202, 203, 218, 219, 220, 236 and 237 and the corresponding files examined. These bores were treated in the same way as the published ones and plotted on the 1 in. to a mile tracings. Many bores stopped in the Kelloways Beds or Cornbrash, these have been extrapolated to the bottom of the Cornbrash by taking means of the thicknesses for neighbouring bores. A list of bores is given in table 7; column 1 gives the name of the parish, columns 2, 3 and 4 the latitude, longitude and surface height. Column 5 gives the height above Ordnance Datum of the base of the Cornbrash, and column 6 that of the base of the Great Oolite Limestone, column 7 gives the thickness

* Only two sheets of the new series maps have been issued in this area (No. 203 Bedford and the special Oxford sheet).

† We are indebted to Mr Edmunds and his staff for preparing this list and for allowing us to abstract the data.

TABLE 7. BORE-HOLES

1	2	3	4	5	6	7	8	9	10	11	12
				Above O.D.		Thicknesses					
Parish	Lat. N	Long. W	Ht. ft.	Cornbrash	Great Oolite Limestone	Great Oolite	Inferior Oolite	Upper Lias	Middle and Lower Lias	Rhaetic and Trias	Source[1]
Bourn 15	52° 47·2′	0° 16·9′	9	− 80	−112	32	—	—	—	—	WSL
,, 16	46·7	17·5	8	− 84	−114	30	—	—	—	—	,,
,, 17	46·7	16·7	7	−113	−144	31	—	—	—	—	,,
,, 5	46·1	22·3	30	+ 2	− 45	47	—	—	—	—	,,
,, 6	46·0	22·2	22	+ 6	− 26	32	—	—	—	—	,,
,, 3	46·0	23·0	40	+ 17	− 17	34	—	—	—	—	,,
,, 8	46·0	22·5	30	+ 16	− 19	35	—	—	—	—	,,
,, 10	45·9	24·0	134	+ 63	+ 34	29	—	—	—	—	,,
,, 13	45·9	20·2	9	− 41[2]	—	—	—	—	—	—	,,
,, 14	45·8	20·3	10	− 44	− 74	30	—	—	—	—	,,
,, 4	45·8	22·6	30	− 2	− 28	26	—	—	—	—	,,
,, 7	45·8	22·5	30	− 6	− 33	27	—	—	—	—	,,
Toft	45·5	23·9	100	+ 6	− 25	31	—	—	—	—	,,
Thurlby 5	45·3	21·8	20	+ 9	− 19	28	—	—	—	—	,,
,, 7	44·7	21·8	29	+ 5	− 23	28	—	—	—	—	,,
Bourn 18	44·6	15·9	8	−116	−146	30	—	—	—	—	,,
Thurlby 8	44·3	22·7	70	+ 46	+ 19	27	—	—	—	—	,,
,, 4	44·2	21·9	28	+ 14	− 16	30	—	—	—	—	,,
,, 6	44·2	22·5	29	+ 7	− 27	34	—	—	—	—	,,
,, 2	43·6	21·6	33	+ 1	− 29	30	—	—	—	—	,,
Deeping St Nicolas	43·6	12·2	10	−223	−253	30	—	—	—	—	,,
Thurlby 1	43·3	21·6	24	+ 12	− 17	29	—	—	—	—	,,
Wilsthorpe 2	43·2	24·0	58	—	43	—	—	—	—	—	,,
Deeping St Nicolas	43·2	16·8	8	−119	−146	27	—	—	—	—	158/51
Langtoft	43·2	17·0	10	−115	−143	28	—	—	—	—	WSL
Baston 1	(43	19)	12	− 72	−103	31	—	—	—	—	,,
,, 2	(43	18·5)	12	− 92	−126	34	—	—	—	—	,,
Cottesmore	(43	39)	445	—	—	—	—	214?	—	—	157/72
Wilsthorpe 1	42·7	23·7	55	+ 51	+ 22	29	—	—	—	—	WSL
Deeping St Nicolas	42·6	14·3	10	−176	−205	29	—	—	—	—	158/45
,, ,, ,,	42·5	14·0	9	−185	−211	26	—	—	—	—	158/48
Braceborough	42·3	24·0	54	+ 14	− 17	31	—	—	—	—	WSL*
Deeping St Nicholas	42·1	15·5	10	−201	−229	28	—	—	—	—	158/49
Greatford	41·6	23·7	45	+ 19	− 9	28	—	—	—	—	157/69
,,	41·6	23·8	40	+ 22	− 7	29	—	—	—	—	157/69

See notes at end of table.

TABLE 7 (*continued*)

1	2	3	4	5	6	7	8	9	10	11	12
				Above O.D.		Thicknesses					
Parish	Lat. N	Long. W	Ht. ft.	Cornbrash	Great Oolite Limestone	Great Oolite	Inferior Oolite	Upper Lias	Middle and Lower Lias	Rhaetic and Trias	Source
Great Casterton	52° 41·5′	0° 30·5′	252	—	211	—	—	—	—	—	WSR*
Crowland	40·6	10·0	12	−202	−238	36	58	135	—	—	WSL
Market Deeping	40·5	18·9	30 }	− 14?	− 40	26?	—	—	—	—	158/50
,, ,,	40·5	18·9	20 }	− 20	− 49	29	—	—	—	—	WSL
Deeping St James	40·4	13·9	10	−132	−158	26	—	—	—	—	158/46
,, ,, ,,	40·3	18·1	12	− 24	− 53	29	—	—	—	—	158/43
,, ,, ,,	40·2	17·0	10	− 33	− 64	31	—	—	—	—	WSL
,, ,, ,,	40·1	14·6	13	−104	−129	25	—	—	—	—	158/44
Deeping, West	39·8	21·6	40	+ 8	27	35	—	—	—	—	WSL
Deeping St James	39·7	14·2	12	−100	−120	20	—	—	—	—	158/47
Stamford	39·6	28·8	188	—	160	—	—	—	—	—	157/64
Uffington	39·4	26·1	114	+109	+ 76	33	—	—	—	—	WSL
Borough Fen	39·2	14·1	12	−104	−132?	28?	—	—	—	—	158/31
Hambleton	(39	40)	—	—	—	—	—	176	—	—	WSR
Stamford	38·9	28·3	95	—	—	—	—	193	—	—	WSL
Peakirk	38·8	16·5	22 }	− 46	− 71	25	—	—	—	—	158/29
,,	38·7	16·2	25 }	− 40	− 66	26	—	—	—	—	WSN*
Etton 4	38·6	18·9	30	− 11	− 38	27	—	—	—	—	WSN
Bainton	38·6	23·1	54	+ 29	− 6	35	—	—	—	—	157/8
Barnack	38·5	25·1	77	+ 63	+ 29	34	—	—	—	—	157/16
Glinton	38·3	17·6	30	− 8	− 40	32	—	—	—	—	WSN
Barnack	38·3	25·4	163	—	+157	—	86	—	—	—	157/5
Edith Weston	38·3	37·8	350	—	—	—	—	163?	—	—	157/40
Newborough	38·2	13·2	10	− 93	−112	19	—	—	—	—	WSN*
Helpston 2	38·1	20·9	61	+ 58	+ 27	31	—	—	—	—	,,
Manton	(38	42)	275	—	—	—	—	168	—	—	157/37
Ketton	(38	34)	250	—	—	—	—	99?	—	—	WSR
Easton	(38	30)	—	—	—	—	—	80?	—	—	157/10
Thorney	37·9	08·8	11	−152	−189	37	74[3]	—	—	—	WSC
Glinton 3	37·8	16·9	30 }	− 14	− 39	25	—	—	—	—	WSN
,, 4	37·8	16·9	30 }	− 18	− 43	25	106	—	—	—	,,
Helpston	37·8	20·6	40	—	− 22	—	—	—	—	—	158/30
Etton 1	37·8	18·8	25	—	− 13	—	—	—	—	—	WSN
,, 2	37·8	18·8	25 }	+ 16	− 12	28	—	—	—	—	,,
,, 3	37·8	18·8	25 }	+ 15	− 15	30	—	—	—	—	,,

Helpston	52° 37·6′	0° 18·9′	26	—	− 8	—	—	—	—	—	WSN*
Etton	37·6	18·9	26	—	− 16	—	—	—	—	—	158/7
Glinton 1	37·0	17·2	35	− 1	− 26	25	—	—	—	—	WSN
Preston	(37	43)	420?	—	—	—	—	160?	—	—	157/36
Wittering	(37	27)	220?	—	—	—	—	73	—	—	157/15
Marholm 1	37·0	17·7	30	+ 1	− 24	25	—	—	—	—	WSN
,, 2	37·0	17·7	30	+ 2	− 28	30	97	—	—	—	,,
North Luffenham	(37	37)	250	—	—	—	—	198	—	—	157/38
Werrington 1	36·9	17·4	31	− 15	− 39	24	—	—	—	—	WSN
,, 2	36·9	17·4	31	− 16	− 45	29	—	—	—	—	,,
,, 3	36·9	17·4	31	− 13	—	—	—	—	—	—	,,
Eye	36·5	11·3	22	− 53	− 74	21	50	—	—	—	WSN*
Walton 1	(36·2	16·2)	40	+ 36	+ 13	23	56	—	—	—	WSN
,, 2	(36·2	16·2)	48	+ 47	+ 19	28	52	—	—	—	,,
South Luffenham	(36	37)	205	—	—	—	—	174?	—	—	157/39
Peterborough 1	35·8	14·2	45	− 20	− 41	21	48	—	—	—	WSN*
,, 2	35·6	15·2	52	+ 44	+ 22	22	142?[4]	109?[4]	—	—	WSN
,, 3	35·6	15·2	52	+ 46	+ 26	20	—	—	—	—	,,
,, 4	35·6	15·2	52	+ 45	+ 24	21	—	—	—	—	,,
Uppingham	(35	43)	490	—	—	—	—	212	—	—	WSR
Fineshade	34·4	33·4	252	249	219	30	—	—	—	—	157/13
Castor	(34	21)	—	—	—	—	23	117?	—	—	WSN
Laxton	(33	36)	—	—	—	—	109	—	—	—	171/41
Southery	32·6	29·6 E	10	−471[5]	—	8[5]	0	0	—	—	SP22
Farcet	(32·2	13·7)	27	− 46	− 69	23	—	—	—	—	WSH
Doddington	32·0	03·6 E	27	−169?[6]	—	—	—	—	—	—	WSC*
Brigstock 14	(29	34)	—	—	—	—	49	—	—	—	WSN
Ashton	28·7	23·8	236	97	70	27	44	—	—	—	WSN
Benefield	28·5	34·9	296	206	—	—	—	—	—	—	171/12
Bury	27·2	06·8	32	−133[9]	—	—	—	—	—	—	WSH*
Ramsay	26·7	06·8	30	−133	—	—	—	—	—	—	,,
Desborough 4	26·3	49·8	359	—	—	—	—	212[7]	—	—	WSN
Woodwalton	26·4	12·7	10	− 70[8]	—	—	—	—	—	—	172/15
,,	26·1	12·6	10	− 79[8]	—	—	—	—	—	—	172/14
,,	26·0	13·0	10	− 67[8]	—	—	—	—	—	—	172/11
,,	26·0	13·5	10	− 69[8]	—	—	—	—	—	—	172/10
,,	25·9	13·3	10	− 69	—	—	—	—	—	—	172/12
,,	25·9	12·8	10	− 75[8]	—	—	—	—	—	—	172/13
Great Oxendon	26·1	55·2	385	—	—	—	—	—	665	82	SP34
Clapton 2	24·8	27·2	230	45?	—	—	—	—	—	—	WSN*

See notes at end of table.

TABLE 7 (*continued*)

1	2	3	4	5	6	7	8	9	10	11	12
				Above O.D.		Thicknesses					
Parish	Lat. N	Long. W	Ht. ft.	Cornbrash	Great Oolite Limestone	Great Oolite	Inferior Oolite	Upper Lias	Middle and Lower Lias	Rhaetic and Trias	Source
Kettering 4	52° 24·7′	0° 44·1′	295	—	—	—	—	163[13]	—	—	WSN
Clapton 1*a*	24·5	26·2	244	− 13	− 39	26	67	—	—	—	,,
Orton	24·2	49·0	375	—	—	—	—	—	531	49	,,
Abbots Ripton 1	23·0	10·5	87	−122	—	—	—	—	—	—	WSH*
Woodford	22·4	36·9	275	—	218	—	55	—	—	—	WSN*
Burton Latimer	21·8	38·9	266	—	223?	—	—	182	—	—	WSN
Raunds 1	20·7	32·6	204	—	184	—	14	—	—	—	,,
,, 8	(20·5	32·7)	116	—	—	—	—	156[17]	—	—	,,
,, 3	(20·2	32·8)	200	196?	162?	34?	15	—	—	—	,,
,, 6	20·5	31·5	220	208	—	—	—	—	—	—	,,
,, 7	19·8	29·9	246	163[9]	—	—	—	—	—	—	,,
Irthlingborough 1	(19·5	37)	270	—	210	—	17	—	—	—	,,
,, 2	(19·5	37)	247	—	207	—	47	—	—	—	,,
Higham Ferrers 1	18·6	34·0	271	—	194	—	—	—	—	—	,,
Long Buckby 2	18·6	1 03·0	580	—	—	—	—	184	—	—	,,
Brington	17·8	1 02·1	465	—	—	—	—	180	—	—	,,
Stonely	17·5	0 22·6	103	25	+ 1	24	48	—	—	—	186/101
Wilby	17·4	43·3	228	—	224	—	41	—	—	—	WSN
Pertenhall	16·9	24·2	205	53[6]	—	—	—	—	—	—	WSB*
,,	16·9	24·3	160	45	25	20	10	—	—	—	186/85
Newton Bromswold	16·9	32·3	285	208?	—	—	—	—	—	—	186/64
Great Staughton	16·6	19·9	102	− 8	—	—	—	—	—	—	187/84
,, ,,	16·3	19·2	88	− 14	—	—	—	—	—	—	187/83
Rushden 1	(16·3	35·1)	311	245	221	24	15	—	—	—	WSN
Moulton	16·3	51·8	410	—	387	—	78[16]	—	—	—	,,
Graveley	15·6	10·3	154	−150	—	—	—	—	—	—	WSC
Podington	15·1	36·7	300	—	276?	—	—	—	—	—	186/91
Upton 1	14·6	57·4	390	—	—	—	—	190	—	—	WSN
,, 5	14·6	57·4	362	—	—	—	—	183	—	—	,,
Keysoe	14·6	24·0	252	155?[6]	—	—	—	—	—	—	WSB*
Northampton 21	(15	52·5)	278	—	—	—	—	153[13]	567	67	WSN
,, 23	14·2	53·6	—	—	—	—	—	156[13]	—	—	,,
,, 20	14·1	52·8	246	—	—	—	—	139[13]	—	—	WSN*
,,	14·1	53·4	—	—	—	—	—	146	—	—	185/47
St Neots	13·6	16·1	51	− 55?	—	—	—	—	—	—	187/30

Great Houghton 2	52° 13·0′	0° 50·2′	349	—	316	—	44	—	—	—	WSN*
Hardingstone	(13	53)	347	—	—	—	—	148	—	—	202/39
Bozeat	12·1	41·3	360	—	240?	—	—	—	—	—	WSN
Milton Ernest	(11·6	30·3)	200	165	—	—	—	—	—	—	WSB
Gayton	(11	58)	282	—	—	—	—	—	573	118	WSN
Oakley 1	10·3	31·0	160	134	—	—	—	—	—	—	WSB
Clapham 4	10·2	30·2	140	98[9]	—	—	—	—	—	—	,,
Olney 4	10·0	42·0	208	—	190	—	—	—	—	—	WSBu
Roade	09·8	53·1	414	—	336	—	—	—	—	—	202/11
Clapham 5	09·8	28·2	220	108[6]	—	—	—	—	—	—	WSB
Hartwell	09·5	49·6	411	—	345	—	—	112[13]	—	—	WSN*
Roade	09·4	53·7	355	—	—	—	—	132	—	—	202/92
Bromham	09·1	32·8	180	159	127	32	—	—	—	—	WSB
Bedford 2	09·0	28·9	141	101	—	—	—	—	—	—	,,
,, 1	08·9	29·1	110	—	84	—	14	—	—	—	,,
,, 4	08·9	28·0	147 }	87	—	—	—	—	—	—	,,
,, 3	08·8	27·8	106 }	83	—	—	—	—	—	—	,,
,, 9	08·4	27·2	90	76[9]	—	—	—	—	—	—	,,
,, 6	08·3	27·8	100	77	—	—	—	—	—	—	,,
,, 5	08·2	27·8	93	—	36	—	8	—	—	—	,,
,, 8	08·2	28·0	95	—	– 12	—	—	—	—	—	,,
Stagsden	07·9	35·1	225?	140	92	48	—	—	—	—	203/91
Bedford 10	07·7	27·8	107	—	46	—	16	—	—	—	WSB
Hanslope	07·5	50·4	400	—	293	—	—	—	—	—	WSBu
Bedford 11	07·2	28·4	100	64	30	34	—	—	—	—	WSB
Cardington 1	(07	24·5)	87	19[9]	—	—	—	—	—	—	,,
Kempston 1	06·5	32·1	150	78[6]	—	—	—	—	—	—	,,
Northill	06·3	19·3	110	– 95	—	—	—	—	—	—	,,
Wooton 1	06·2	32·2	150	74[6]	—	—	—	—	—	—	,,
Kempston 8	06·2	34·6	200	74	41	33	—	—	—	—	,,
Paulerspury	06·1	56·4	401	—	361	—	—	—	—	—	202/37
Wappenham	(06·0	1 04·8)	—	—	—	—	—	139[14]	—	—	WSN
Wooton 4	06·0	0 32·3	153	76[6]	—	—	—	—	—	—	WSB
,,	06·0	32·3	153	52[6]	—	—	—	—	—	—	,,
,, 7	05·9	31·5	125	44[6]	—	—	—	—	—	—	,,
,, 5	05·8	32·2	160	33[6]	—	—	—	—	—	—	,,
,, 6	05·6	32·0	136	59[6]	—	—	—	—	—	—	,,
Newport Pagnell	05·6	44·7	226	—	172	—	—	—	—	—	,,
Cardington 2	(05·3	24·9)	100	– 26[6]	—	—	—	—	—	—	,,
Willshamstead	(05·2	25·3)	115?	– 2[6]	—	—	—	—	—	—	,,

See notes at end of table.

TABLE 7 (*continued*)

1	2	3	4	5	6	7	8	9	10	11	12
				Above O.D.		Thicknesses					
Parish	Lat. N	Long. W	Ht. ft.	Cornbrash	Great Oolite Limestone	Great Oolite	Inferior Oolite	Upper Lias	Middle and Lower Lias	Rhaetic and Trias	Source
Potterspury	52° 04·6′	0° 55·3′	360?	—	331?	—	—	—	—	—	202/53
Haynes 2	03·9	22·7	271	55	—	—	—	—	—	—	WSB
Marston Moretaine 2	03·8	34·2	160	60[6]	—	—	—	—	—	—	,,
,, ,, 1	03·7	32·9	140	53[9]	—	—	—	—	—	—	,,
Houghton Conquest	03·7	28·5	158	− 44[6]	—	—	—	—	—	—	,,
Newport Pagnell	03·6	41·9	200	145[10]	—	—	—	—	—	—	WSBu
Wolverton	(03·6	48·8)	—	—	—	—	56?	39?	—	—	—
Stony Stratford 2	03·0	51·0	222	—	198	—	17	57	—	—	WSBu
Lillingstone Dayrell	03·0	1 00·0	427	—	319?	—	—	—	—	—	,,
Stony Stratford 1	02·5	0 49·3	291	215?	178	37?	29	55	—	—	,,
Brackley	01·9	1 08·9	471	—	432	—	37	104	—	—	219/3
,,	01·9	08·9	455	—	403	—	8	109	—	—	WSN
Shenley Church End	01·8	0 47·6	305	192	159	33	—	—	—	—	WSBu
Stowe	01·7	1 01·4	406	—	251	—	—	—	—	—	219/69
Hinton in the Hedges	01·7	11·0	455	—	439	—	53	107	—	—	219/5
Maids Moreton 12	01·2	0 58·5	396	274[10]	—	—	—	—	—	—	WSBu
,, ,, 1	00·7	58·8	374	286	232	54	21	68	—	—	,,
,, ,, 2	00·7	58·8	374	281	230	51	21	68	—	—	,,
,, ,,	00·7	58·8	374	277	222	55	19	61	—	—	219/49
Fenny Stratford	51 59·8	42·8	220	84[11]	56	28	0	—	—	—	220/171
,, ,,	59·7	44·0	260	68[11]	35	33	—	—	—	—	WSBu
Buckingham 1	59·7	59·3	260	—	212	—	—	—	—	—	,,
Newton Longville	58·4	46·0	348	113[15]	—	—	—	—	—	—	,,
Chetwode	57·8	1 03·4	340	280[10]	193?	85?	—	—	—	—	,,
Horwood, Little	57·5	0 50·5	400	136	98	38	—	—	—	—	,,
Winslow	56·5	52·8	370	110	—	—	—	—	—	—	,,
Pounden	55·2	1 04·4	382	216[10]	—	—	—	—	—	—	,,
Steeple Claydon	55·0	0 59·9	290	193	94	99	0	0	240	0	,,
Charndon	54·8	1 00·3	222	190[11]	87	103	0	—	245	0	,,
Bicester	54·5	10·5	277	—	169?	—	—	—	—	—	WSO
,,	54·3	09·0	255	247	179	68	—	—	—	—	,,
Marsh Gibbon	54·2	03·5	240	117[10]	—	—	—	—	—	—	WSBu
Grendon Underwood	(53·3	00·7)	280	5[12]	—	—	—	—	—	—	219/73
Blackthorn	52·7	05·7	205	150	—	—	—	—	—	—	WSO
Arncot	51·0	06·5	300	123	48	75	—	—	—	—	,,
Bletchingdon	50·8	14·4	220	128	—	—	—	—	—	—	,,
Stone	48·0	0 52·2	353	− 177?[15]	—	—	—	—	—	—	WSBu
Missenden, Little	40·4	41·9	470	− 562[15]	− 628?	66	—	—	—	—	,,

See notes at end of table.

Notes to Table 7.

WSL	= Geological Survey Memoir on Water Supply of Lincolnshire.					
WSR =	,,	,,	,,	,,	,,	Rutland.
WSN =	,,	,,	,,	,,	,,	Northamptonshire.
WSC =	,,	,,	,,	,,	,,	Cambridgeshire.
WSH =	,,	,,	,,	,,	,,	Huntingdonshire.
WSB =	,,	,,	,,	,,	,,	Bedfordshire.
WSBu =	,,	,,	,,	,,	,,	Buckinghamshire.
WSO =	,,	,,	,,	,,	,,	Oxfordshire.
SP22	= Summary of Progress for 1922.					

An asterisk has been placed after the letters when additional information has been obtained from the Geological Survey about a bore from a Water Supply Memoir.

The numbers are those given to the bores in the files of the Geological Survey, the first figure is the New Series sheet number.

[2] Bottom of Cornbrash assumed 7 ft. below top.

[3] Top of Upper Lias assumed 4 ft. below the bottom of the hole which stopped in the Northampton Sands ironstone.

[4] Northampton Sands assumed 17 ft. thick.

[5] Bottom of Cornbrash assumed 2 ft. below top. No Great Oolite limestone, 10 ft. Cornbrash plus Forest Marble.

[6] Bottom of Cornbrash assumed 22 ft. below top of Kelloways.

[7] Top of Lias from Desborough 1.

[8] Bottom of Cornbrash assumed 7 ft. below top as at Woodwalton 172/12.

[9] Bottom of Cornbrash assumed 2 ft. below top.

[10] Bottom of Cornbrash assumed 8 ft. below bottom of Oxford Clay.

[11] No Cornbrash

[12] Bottom of Cornbrash assumed 5 ft. below top.

[13] Beeby Thompson (1925) has expressed doubts about the thickness of the Upper Lias in this bore.

[14] Assuming bore to have reached bottom of Upper Lias.

[15] Bottom of Oxford Clay.

[16] Top of Upper Lias assumed 18 ft. below the bottom of the hole which stopped in the Northampton Sands ironstone (cf. Moulton 3).

[17] Top of Upper Lias assumed at 156 O.D. from Raunds 1, 3 and 6.

from the bottom of the Cornbrash to the bottom of the Great Oolite limestone, column 8 that from the bottom of the Great Oolite limestone to the top of the Upper Lias, column 9 that of the Upper Lias, column 10 that of the Middle and Lower Lias (which cannot be distinguished in the bore hole logs) and column 11 that of the Rhaetic and Trias. Column 12 gives the source of the information. The positions are generally correct to within 1000 ft., the more doubtful ones being enclosed in brackets. Doubtful surface heights are followed by a ?, and where there is a doubt as to the interpretation of the record, the depth is queried in columns 5 or 6. Contours of the base of the Cornbrash and of the Great Oolite limestone were then drawn at 50 ft. intervals on the tracings. The separation between the two horizons is remarkably constant and is shown in figure 9. By assuming these thicknesses to hold to the west of the present Cornbrash outcrop both sets of data may be represented on one contoured map (figure 8)* showing the base of

* Some of the bores are so close together that they cannot be plotted separately on figure 8. Such bores have been bracketed together in table 7 and the mean plotted. At a few bores the Cornbrash is absent, the base of the Oxford Clay is then taken.

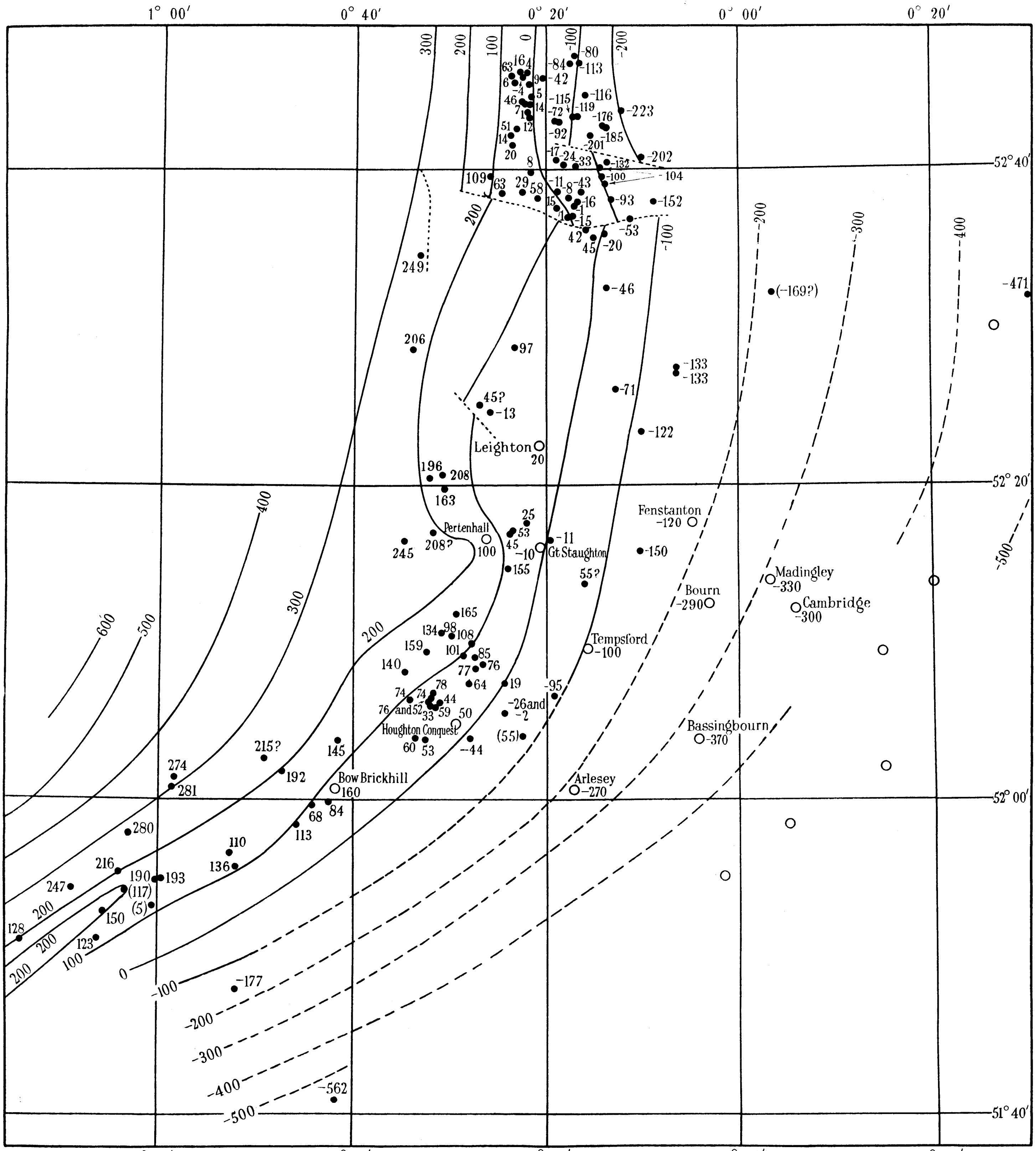


FIGURE 8. Contours of the base of the Cornbrash in feet above O.D. (1 in. = 10 miles, 1: 633600). ● = Bore-holes, ○ = Seismic stations, - - - - = faults. The contours on the west side are derived from the heights of points on the outcrop which are too numerous to show separately on this scale.

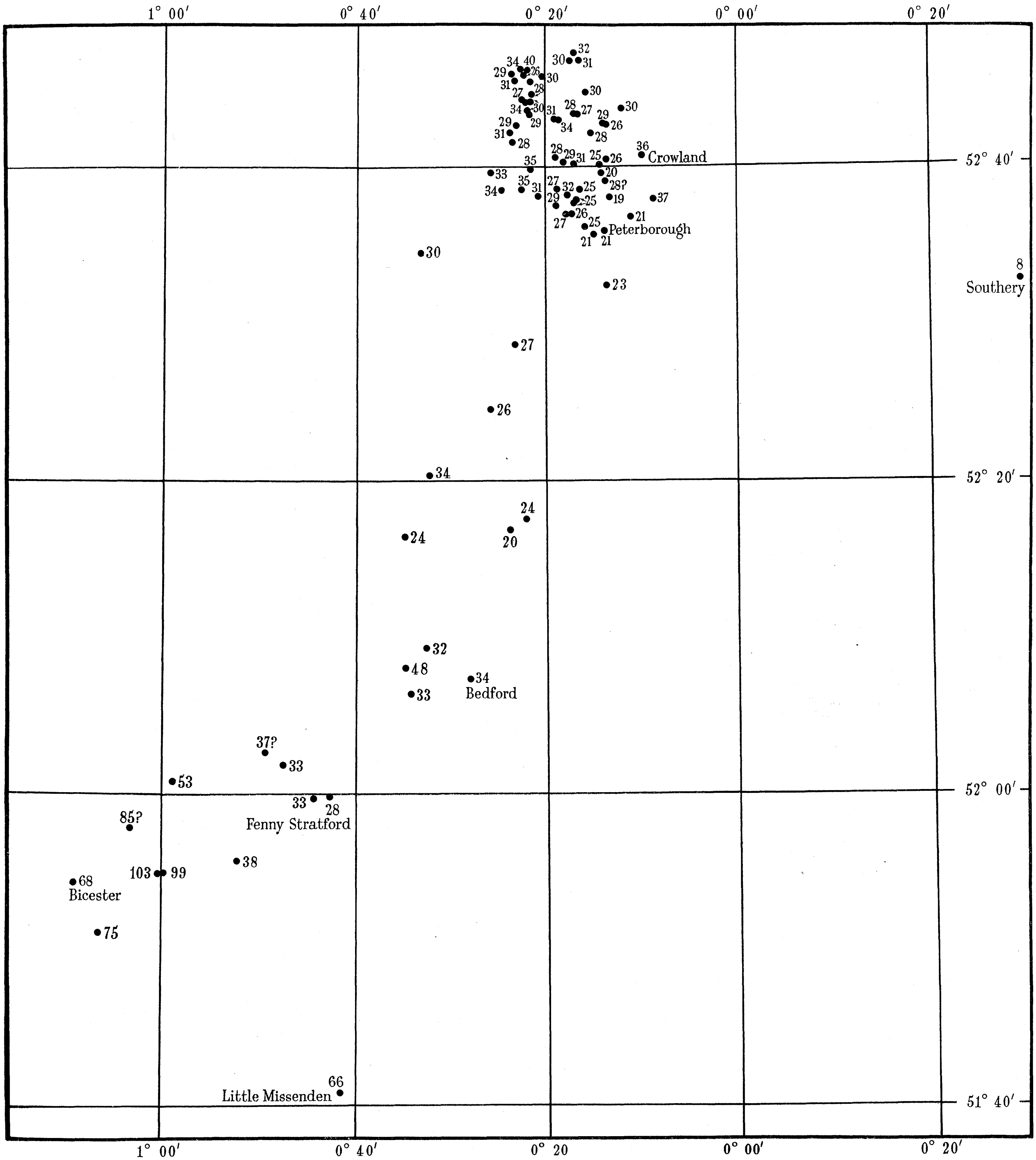


FIGURE 9. Thickness of the Great Oolite in feet (1 in. = 10 miles, 1 : 633600). ● = bore-holes.

the Cornbrash from +600 ft. at the Great Oolite outcrop in the west, to −150 ft. on the east. The depths given by the contours are probably correct within 50 ft., the principal error coming from uncertainties in interpolating between the widely spaced bore-holes. To the south and east of the −150 ft. contour we have only Southery (−471 ft.) and Little Missenden (−570 ft.) and a few bores north-east of Peterborough. To extend the map the seismic results may be used. The upper of the two discontinuities found at each station is shown in figure 8. The results at Leighton, Great Staughton, Pertenhall, Houghton Conquest and Tempsford fit in with the contours very well and leave little doubt that this discontinuity is the transition from the Oxford Clay to the limestones below it. The seismic results are not sufficiently detailed to separate the Kelloways Beds, the Cornbrash, and the Great Oolite limestone. This identification is further strengthened by the fact that the refracted wave from the upper discontinuity at these stations could only be observed at distances less than about 2000 ft., thus indicating a layer of no great thickness. The result at Bow Brickhill is not consistent with the Cornbrash contours (which give +90 ft. compared with the seismic result of +160 ft.). This disagreement is not very serious as there is an exceptional development of limestones at Fenny Stratford $1\frac{1}{2}$ miles to the west.*

It is thus natural to assume that the upper discontinuity at stations farther to the east is due to the same limestones. If this be assumed, the contours of the Cornbrash may be extended to −400 ft. O.D. by the use of these points and the Southery and Little Missenden bores. These contours join smoothly on to those above −150 ft. The bore-holes show a decreasing thickness of limestone towards the east, and it is a little unexpected that the seismic results should indicate that there is still some present as far east as Cambridge. Actually there seems to be more limestone at Cambridge than farther to the west, for the refracted wave from it was observed up to 4000 ft., whilst at Tempsford and Houghton Conquest no observations were possible beyond 2000 ft. It is possible that this thickening is due to the approach to the eastern shore-line of the Jurassic Sea. Alternatively the upper discontinuity under Cambridge may not really be a continuation of that at Tempsford and at Great Staughton. It is difficult to settle this question as the refracted wave is faint and difficult to observe at intermediate stations (Bourn and Fenstanton).

To the west of Cambridge (Fulbourn, Swaffham Prior, etc.) only one discontinuity is observed; the limestones have therefore either thinned out, met the Palaeozoic floor, or got so near it that it is not possible to separate them from it.

It is not possible to apply the same procedure to lower horizons in the Jurassic, as there are not sufficient deep bore-holes in this area. However, the thicknesses of the strata vary less rapidly than their depths below O.D., and a small number of bore-holes suffices to give a general idea of their variation. Combining the thicknesses with the

* The much quoted Bletchley Bore was started at the bottom of a well and nothing is known of the first 148 ft. (to +112 ft. O.D.) below that there are bands of limestone of a total thickness of 55 ft., other bores near this suggest that the limestone bands start above this (Whitaker 1921, p. 135).

depths of the Cornbrash below O.D. then gives a much better representation of the lower strata than would be possible by considering them alone. For this purpose the thicknesses between the bottom of the Great Oolite limestone and the top of the Upper Lias,* between the top of the Upper Lias and the top of the Marlstone, between the top of the Marlstone and the base of the Lower Lias and between the base of the Lower Lias and the Palaeozoic were obtained from bore-holes (table 7), plotted and contoured (figures 10–12). These thicknesses combined with the Cornbrash contours give the actual depth of the top of the Upper Lias, the top of the Marlstone and the base of the Lower Lias.

A contour map of the base of the chalk has also been prepared (figure 13). To construct this the base of the chalk, the Burwell Rock, the Melbourn Rock and the Chalk rock have been treated on a 1 in. to a mile scale in the same way as the Cornbrash (only published bores were used), and by assuming a uniform variation in the thicknesses the whole has been reduced to the base of the chalk. This procedure has been applied in the area shown by the solid line contours in figure 13; only the bores that actually reach the base of the chalk have been plotted though a large number of others have been used. Outside this area a less detailed investigation has been made and the contours have been plotted from the bores shown and from a few lying further to the north. This map differs at some points from one prepared by Morton (1928), the differences are partly due to the larger amount of data used and partly to the correction of errors.

The following bores are inconsistent with the rest and have not been used in the contouring, they are enclosed in brackets on the figures:

Doddington	gives Cornbrash		169 ? ft.	below	O.D.	instead of	220 ft.	below.
Haynes	,,	,,	55 ,,	above	,,	,,	80 ,,	,,
Marsh Gibbon	,,	,,	117 ,,	,,	,,	,,	200 ft.	above.
Grendon Underwood	,,	,,	5 ,,	,,	,,	,,	110 ,,	,,

Thorney	gives thickness	of the	Inferior	Oolite	as 74 ft.	instead of	50 ft.	
Peterborough	,,	,,	,,	,,	142 ? ft.	,,	55 ,,	
Castor	,,	,,	,,	,,	23 ,,	,,	55 ,,	
Clapton	,,	,,	,,	,,	67 ,,	,,	40 ,,	
Wolverton	,,	,,	,,	,,	56 ? ,,	,,	25 ,,	
Brockley	,,	,,	,,	,,	8 ,,	,,	35 ,,	

The contours of the Cornbrash show a smooth surface with an easterly dip of 0·2° in the north, a south-easterly dip of 0·2° in the centre, and a south-south-easterly dip of 0·4° in the south. The Marsh Gibbon and Risley inliers appear as folds with an amplitude of some 50–100 ft. The only considerable feature is a west-north-west to east-south-east system of faults or folds parallel to the Peterborough fault and having a total throw of about 200 ft.

* For typographical convenience in the table and figure headings we have called this the "thickness of the Inferior Oolite" which it strictly is not, as it includes the Upper Estuarine. Similarly we have called the thickness between the base of the Cornbrash and the base of the Great Oolite limestone the "thickness of the Great Oolite".

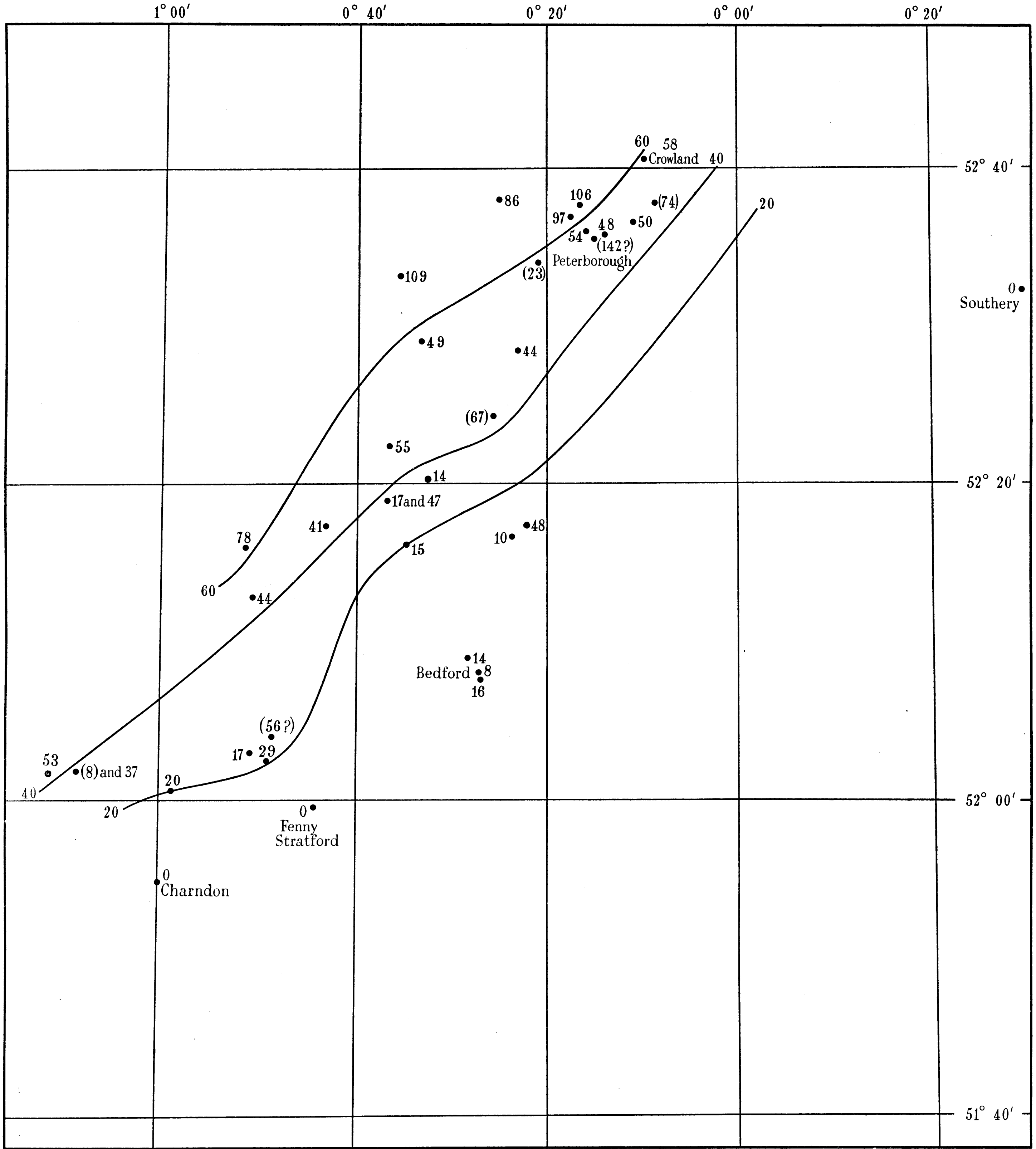


Figure 10. Thickness of the Inferior Oolite in feet (1 in. = 10 miles, 1 : 633600). ● = bore-holes.

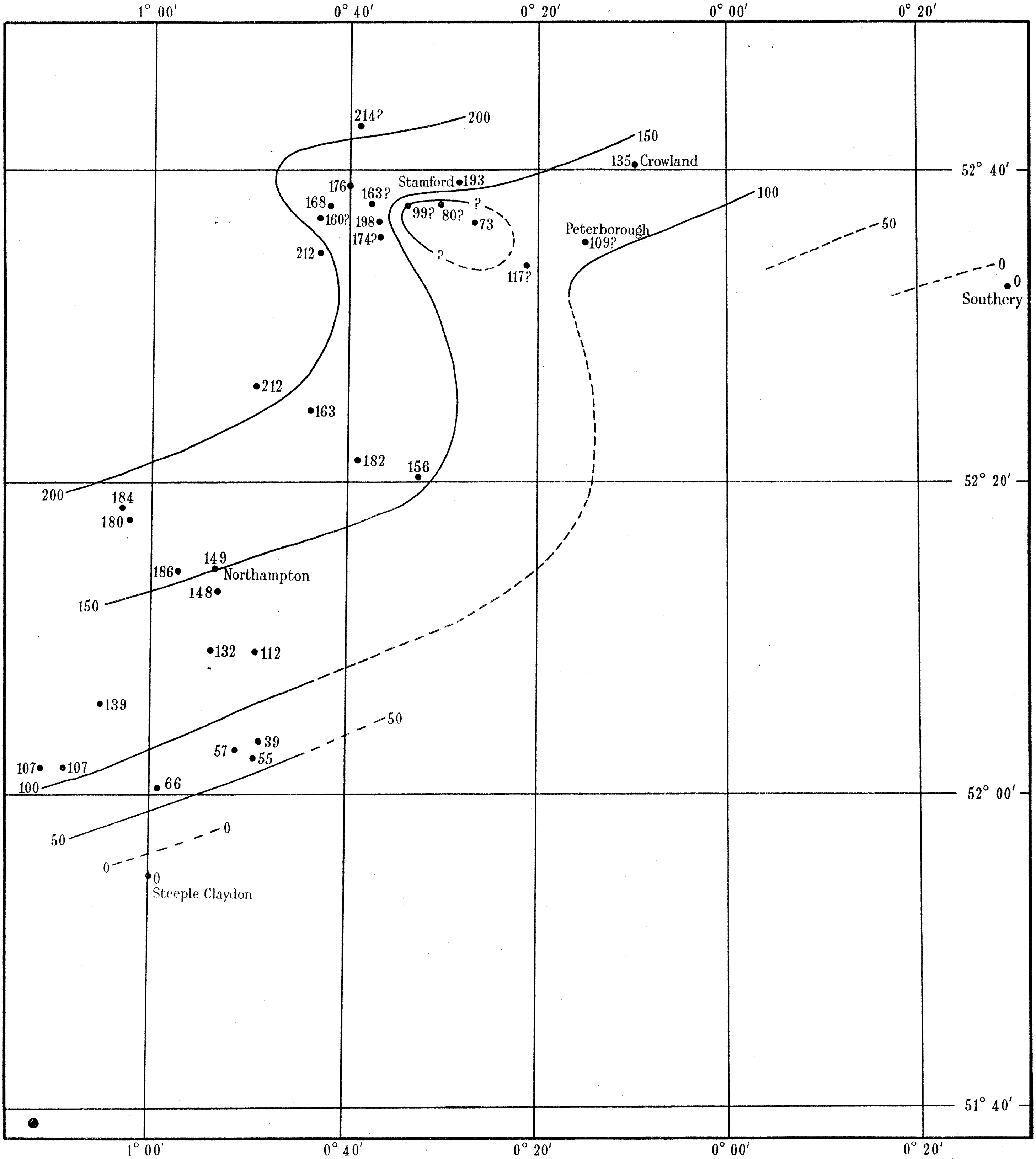


FIGURE 11. Thickness of the Upper Lias in feet (1 in. = 10 miles, 1 : 633600). ● = bore-holes.

There is no indication of folds with a Charnian trend (north-west to south-east). This is remarkable as Rastall (1925, p. 213) has suggested the existence of an anticline with its axis running from Sandy to Orton. This axis was supposed to produce a thinning of the Upper Lias in some parts of Northamptonshire and a thinning of the Greensand near Sandy. The first of these pieces of evidence has been criticized by Beeby Thompson (1925). In order to investigate the second we have plotted the contours of the top and

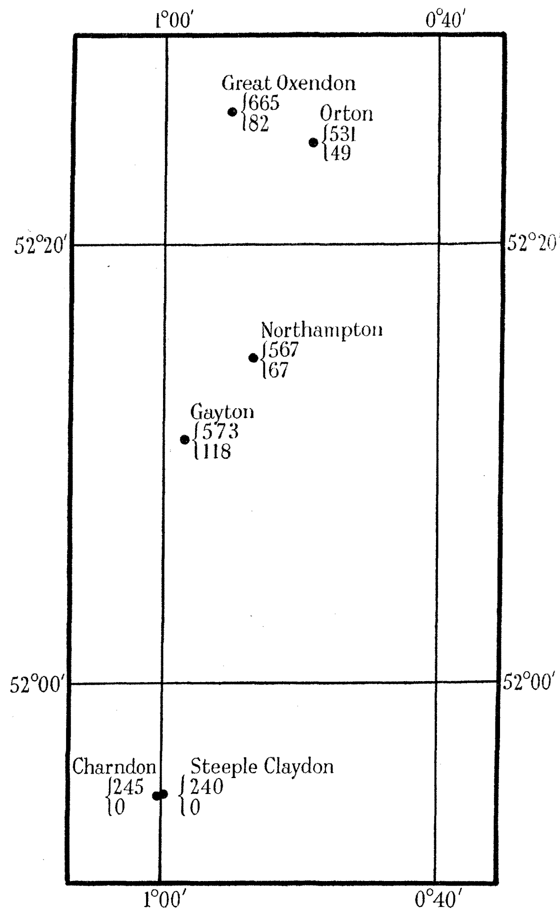


FIGURE 12. Thickness of the Middle and Lower Lias (top figure) and of the Rhaetic and Trias (bottom figure) (1 in. = 10 miles, 1 : 633600). ● = bore-holes.

bottom of the Greensand by the method used for the Cornbrash. The results show that the Greensand is actually thicker near Sandy than a few miles north or south. As this area is being remapped by the Geological Survey on the 6 in. scale it would be unprofitable to discuss the matter further at present, but there seems to be little evidence for folds of Charnian trend in the Mesozoic rocks anywhere in East Anglia; even the usually assumed extension of a north-west—south-east axis from Charnwood to Orton and Great Oxendon is rendered very dubious by a bore at Leicester, which is exactly on the same line and shows Cambrian at 527 ft. below O.D.

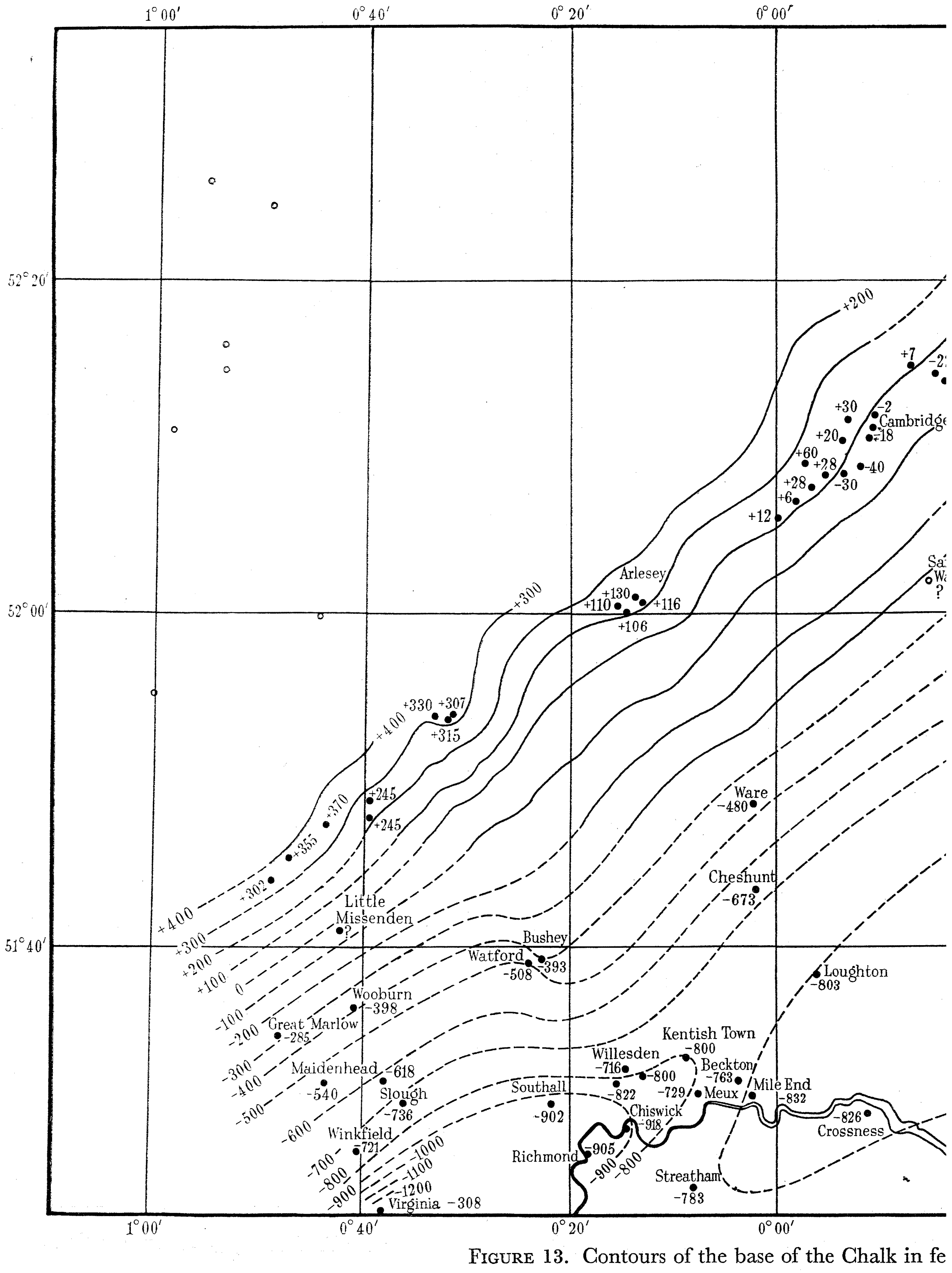
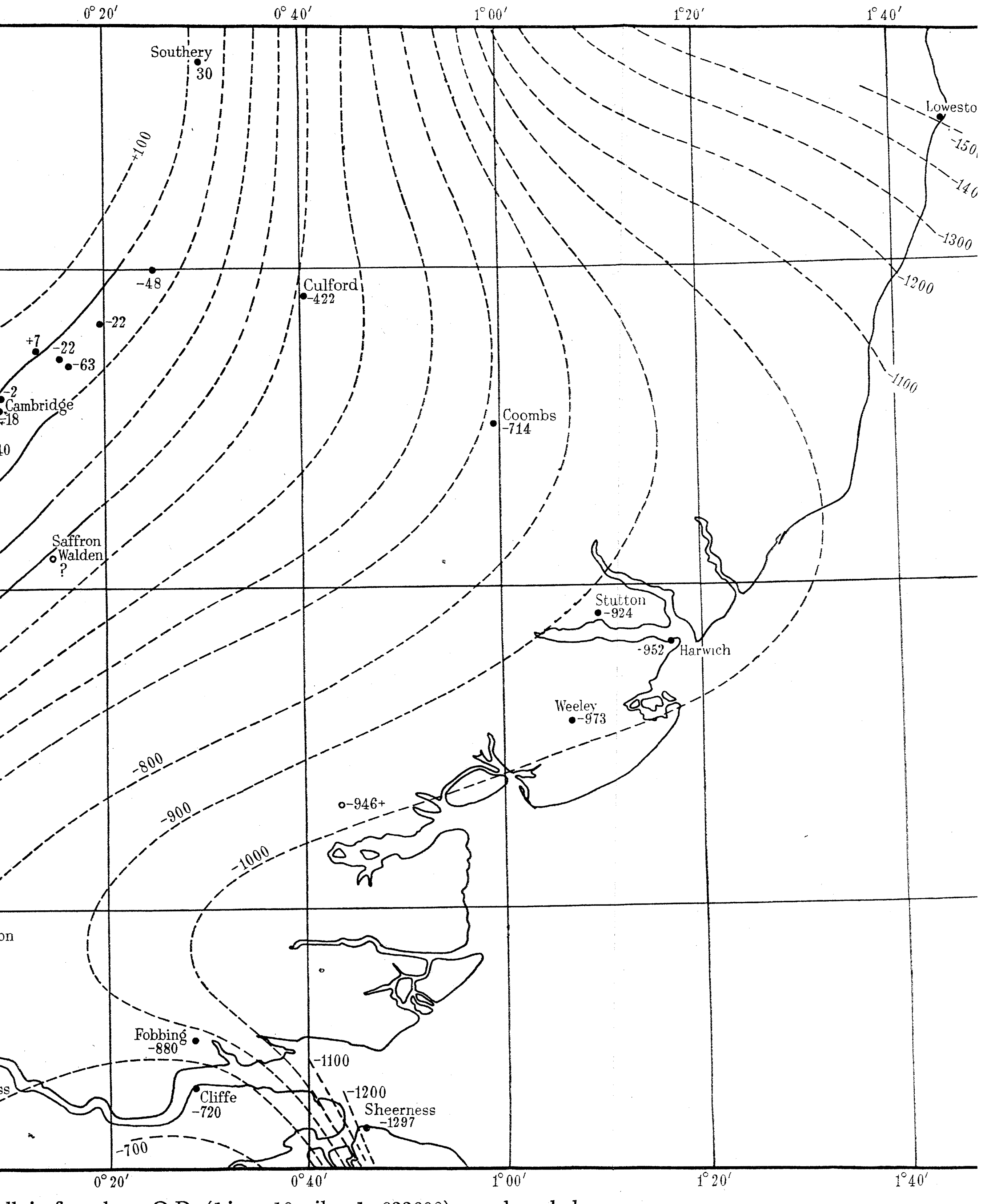
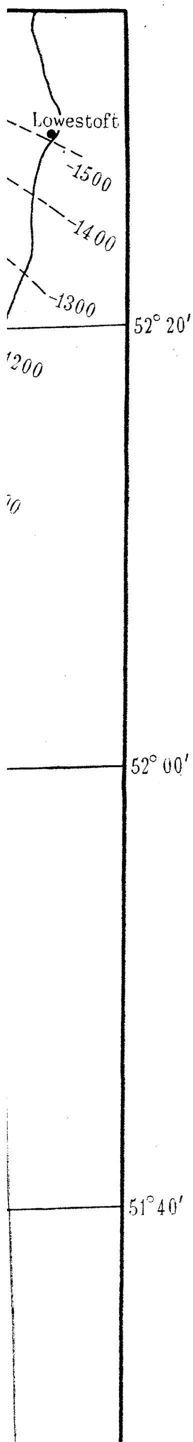


Figure 13. Contours of the base of the Chalk in fe



alk in feet above O.D. (1 in. = 10 miles, 1 : 633600). ● = bore-holes.

facing p. 8



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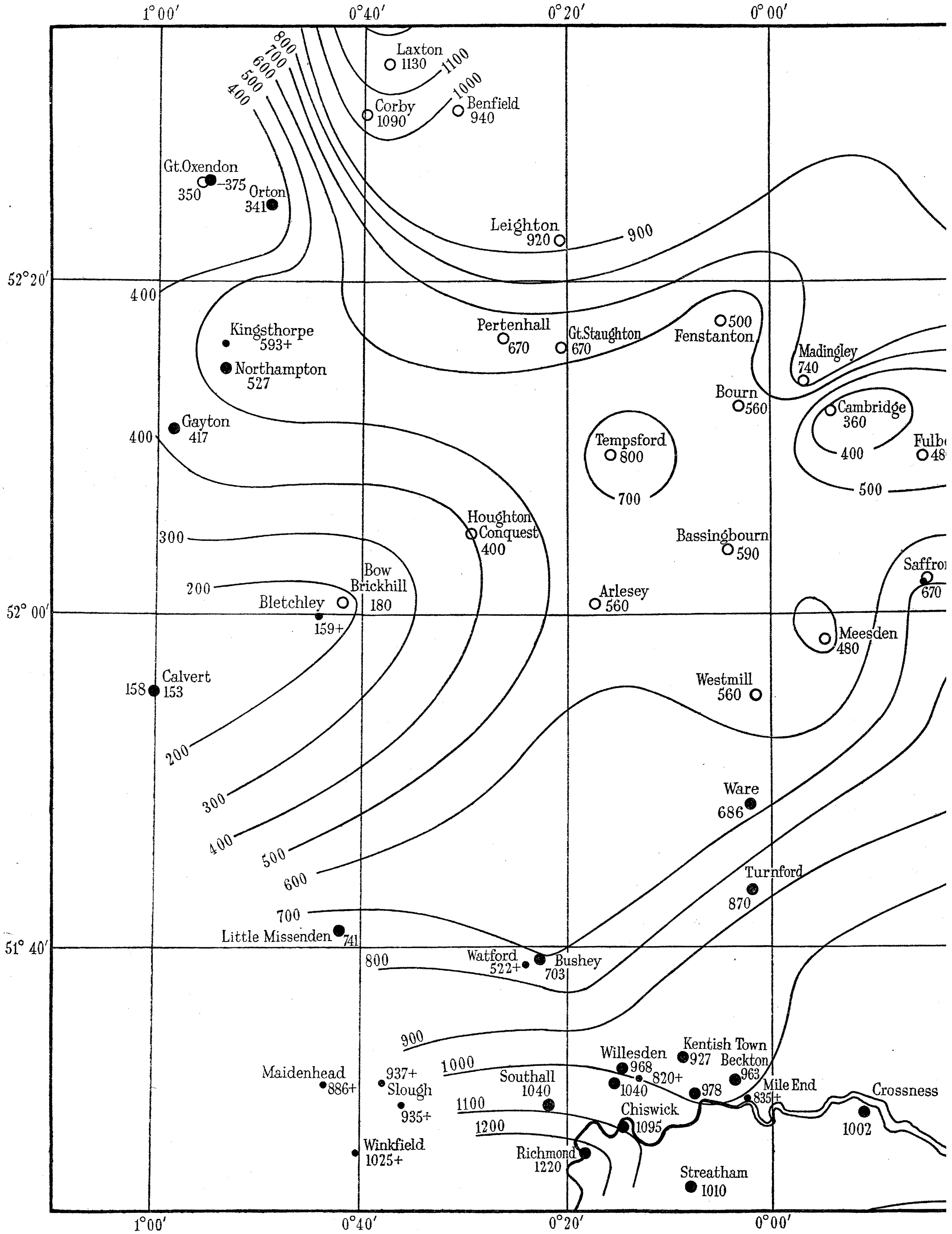
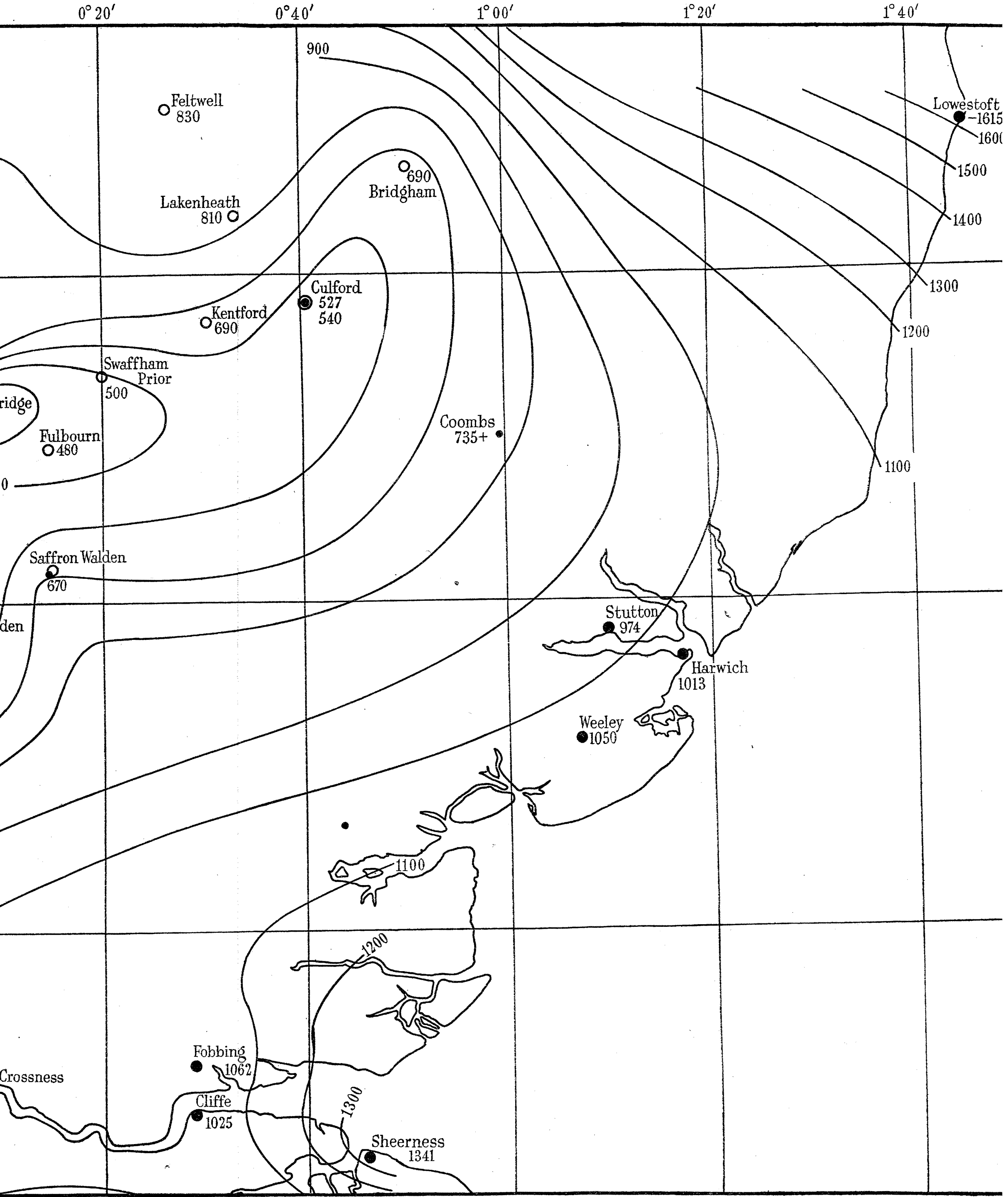
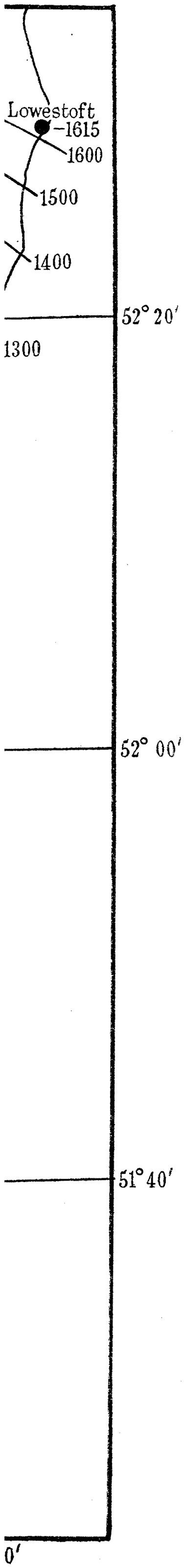


FIGURE 14. Contours of the Palaeozoic floor in feet below O.D. (1 in. = 10 miles, 1 : 633600).



3600). ● = bore-holes reaching the Palaeozoic, • = bore-holes not reaching the Palaeozoic, ○ = seismic statio



c stations.

13. Contours of the Palaeozoic floor

If the upper discontinuity at the western stations is the boundary between the Oxford clay and the limestones below it, the lower discontinuity at these stations and the corresponding discontinuity at the others is almost certainly the surface of the Palaeozoic. This identification is supported by the Culford, Great Oxendon and Bletchley* bores, and by the fact that the refracted wave can be observed to the end of the lines, indicating that it is not produced by a thin layer. The stations are sufficiently closely spaced for it to be unlikely that the floor has been lost by a wrong correlation between stations. The contours of the floor derived from the seismic work and from the bore-holes are shown in figure 14. A list of bore-holes reaching the Palaeozoic is given by Strahan (1913*a*) to which may be added Bushey, Fobbing, Little Missenden and Great Oxendon (Summary of Progress, 1916, 1925, 1933 and 1936). In some areas such as Essex and east Suffolk, the form of the floor is only vaguely known and further work will doubtless alter the contours considerably.

14. Relation of the Mesozoic rocks to the Paleozoic floor

In order to illustrate the way in which the Mesozoic rocks lie against the Palaeozoic floor the sections shown in figure 15 have been prepared. In making these sections the Palaeozoic floor has been taken from figure 14, the Cornbrash from figure 8, the bottom of the Chalk from figure 13, the thicknesses of the Jurassic from figures 9–12, and the thickness of the Gault from Morton. At the eastern end of the sections the thicknesses of the Jurassic can only be inferred on somewhat unsatisfactory evidence which may be summarized thus:

(*a*) The Estuarine Beds thin so rapidly eastwards and southwards (figure 10) that they are unlikely to extend far south-east at Bedford. They are absent at Charndon, Fenny Stratford and Southery.

(*b*) The same applies to the Upper Lias but as it is two to three times as thick as the Estuarine it is likely to extend somewhat farther.

(*c*) The Middle and Lower Lias (which cannot be separated in the bore-holes) are 500–600 ft. thick in Northamptonshire, thin southwards and are absent under London. The thickness at Southery is unknown (112+ft.).

(*d*) The Rhaetic and Trias are 50–120 ft. thick in Northamptonshire and presumably disappear altogether a few miles to the east of the bores shown in figure 12. Only at Corby does the seismic work suggest the presence of Trias.

These facts strongly suggest that the Lower Lias lies on the Palaeozoic over most of the area between Northampton and Cambridge, and that over the eastern half of this area it is succeeded by the Great Oolite limestone. The relations are illustrated diagram-

* Whatever may be the shortcomings of this bore (see above), it is highly probable that it nearly reached the Palaeozoic.

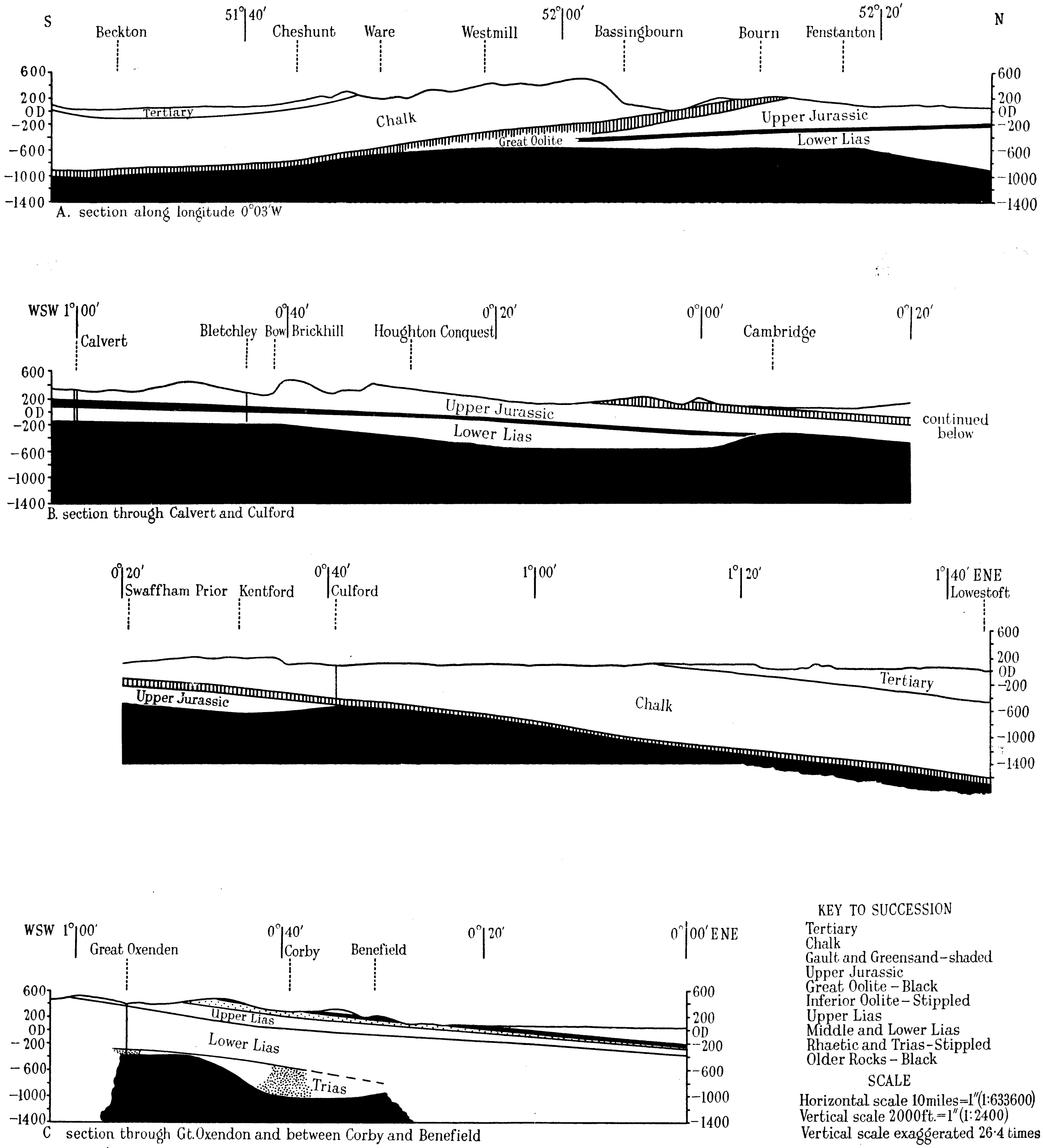


FIGURE 15. Sections compiled from figures 8–14.

matically on a greatly exaggerated vertical scale in figure 16. The most doubtful point in this scheme is the identification of the hard band under Cambridge with the Great Oolite limestones farther west. The northern part of figure 16 shows a striking similarity to Lamplugh, Kitchin and Pringle's section from the Wealden Trough on to the London landmass derived from deep borings (1923). The latter is summarized by Arkell (1933, p. 544) and the southern part of figure 16 has been sketched in from his figure 91. It shows the same transgression of the Lias beyond the Trias and of the Great Oolite beyond the Lias.

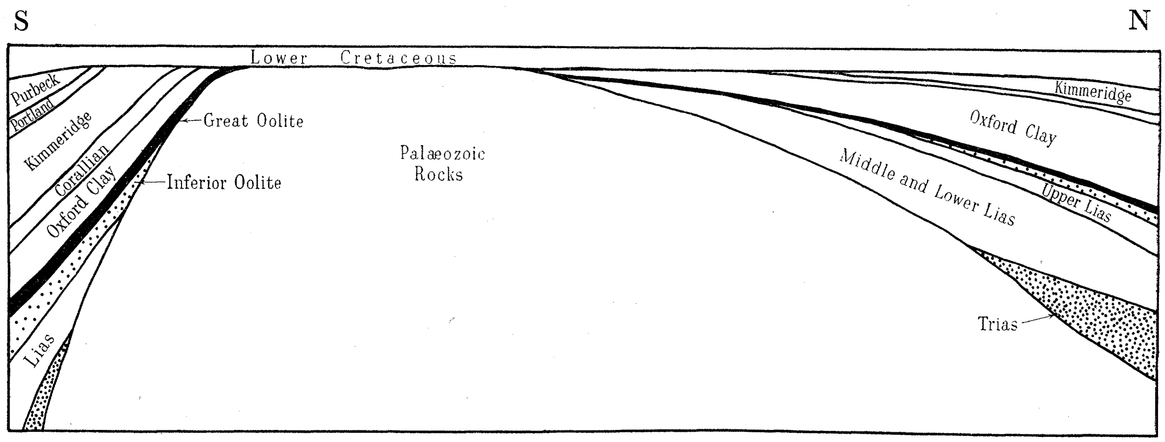


FIGURE 16. Diagrammatic section from the Weald to Northamptonshire. Vertical scale 50 times horizontal.

The Palaeozoic rocks of East Anglia therefore formed a shore line gradually moving eastwards, against which the Jurassic rocks were laid down, and apart from the general tilting and gentle bending they do not seem since then to have suffered any great distortion in the area we have studied. The irregularities in the floor are not reflected in the structure of the Mesozoic.

15. THE NATURE OF THE PALAEOZOIC FLOOR

Figure 14 shows a platform of Palaeozoic rocks under East Anglia at a depth of about 500 ft. below the present sea-level. This platform possesses very gentle relief and the surface slopes gradually downwards in all directions reaching 1000 to 1500 ft. below sea-level round the present coast line. Outside the area of figure 14 it slopes further to below 6000 ft. in the Hampshire Basin and elsewhere.

In most of the bore-holes that reach the Palaeozoic there is evidence of marine transgression without coarse basal deposits. This indicates that the Palaeozoic rocks were reduced to their ultimate peneplane by marine denudation but in some cases this has not removed the whole of the weathered zone.

The number of bore-holes is inadequate to give any detailed picture of the structure of the Palaeozoic rocks, but by combining what evidence there is with the velocities of elastic waves found from the seismic work some conclusions may be reached.

It is now many years since the material from most of these bores was examined and we have therefore re-examined most of it and obtained the opinion of specialists on the fossils found; we are greatly indebted to Dr Stubblefield for assistance in this part of the work. The bores are treated in three groups, first, those in Suffolk and near Harwich, secondly, those near London, and thirdly, those in the western part of the area. The depth of the Palaeozoic floor is given in figure 14 and its nature is shown in figure 17.

The Harwich group

The rocks from these bores are lithologically similar. They appear to have been deposited as silts and mudstones in geosynclinal conditions and the graded bedding and some evidence of contemporary slumping in three of them suggest that there may be great thicknesses, by analogy with the Welsh Ludlow.

The palaeontological evidence is not conclusive but the age is certainly lower Palaeozoic and is probably in part upper Silurian.

Weeley. Palaeozoic 1040 ft. below O.D. beneath Gault (*Rep. Roy. Comm. Coal. Suppl.* 1905; Strahan 1913 *a*, 1916; Whitaker 1916).

These rocks were stated to be Silurian (Strahan 1913 *a*) but there is no palaeontological evidence. There are eight small specimens in the Geological Survey Museum, in the Sedgwick Museum two lengths of core were found: (*a*) 1150–1152 ft. and (*b*) 1130 ft., and in the Ipswich Museum there are two further lengths: (*c*) 1141 ft., (*d*) 1156–1159 ft. below the surface (45 ft. above O.D.).

Specimens from the surface of the Palaeozoic are of a mottled green and red micaceous mudstone with occasional worm tubes filled with white quartz sand. This is underlain by a fine grained structureless mudstone which shows in one specimen a ripple shear effect and in specimens from 1120 and 1130 ft. a very well developed graded bedding. In this the same characteristics are repeated fairly regularly in less than a centimetre. There is a pitted erosion surface covered by coarse sediment showing micro-false bedding which is clearly a winnowing effect. This is followed by a homogeneous gradation from the coarse silt to a very fine grained mudstone. The bedding planes dip at about 70° and cleavage planes with similar strike dip at 30°.

Specimen (*a*) is worthy of a more detailed description and its discovery initiated the search amongst the other cores.

It is a cylinder of rock two feet long, with a diameter of $4\frac{1}{2}$ in. and shows the most complex small-scale structures.

The core was sectioned and a miniature tectonic study made of the recumbent folds, nappes, thrusts, involutions, disharmonic folding, unconformities and facies differences. Figure 22, plate 7 shows a photograph of a section.

There are two main facies types:

(1) The most conspicuous units consist of a light coloured extremely fine-grained mudstone with graded bedding and erosional surfaces occasionally amounting to angular unconformities.

The bedding shows up the structures mentioned above which may be quite isolated. Even so the order of deposition within each unit can be deduced from the graded bedding, micro-false bedding and erosion surfaces. These folds have clearly been formed when the deposit was in a plastic condition, and judging from their shape there has been little or no compaction during their subsequent consolidation (Jones 1939).

(2) The other extreme facies type consists of a coarse structureless micaceous silt which encloses and permeates the other units. It forms a structureless matrix which appears to have been in a fluid or slurry state when mixed with the other units. Incorporated in this matrix are many detached and folded wisps of a medium grade, closely bedded series.

There is abundant evidence in this one specimen to demonstrate that contemporaneous disturbances have produced a mixing of facies when some of the sediments were nearly compacted but still plastic. Specimens (*c*) and (*d*) show similar structures.

Stutton. Palaeozoic 974 ft. below O.D. beneath Gault (Jukes-Browne 1896; *Roy. Comm. Coal. Suppl.* 1905; Whitaker 1906; Strahan 1913*a*, 1916).

Jukes-Browne (1896) mentions the discovery of an undetermined *Orthoceras*. The Palaeozoic is described (Whitaker 1906) as "Silurian or Older" rocks consisting of 16 ft. 6 in. of finely bedded grey calcareous sandstone or mudstone dipping at 45° and underlain by 515 ft.+of "hard bedded, sometimes cleaved, crushed and contorted rocks, with a high dip—sometimes vertical". Specimens in the Sedgwick, Ipswich and Geological Survey Museums show alternations of dark, sometimes slickensided, mudstones with thin silty bands and occasionally thin greywacke grit. They also show graded bedding and Jones compares them with the Ludlow of Denbighshire.

Stubblefield has re-examined the Survey material and reports (MS. 17. v. 39):

"...spec B983, labelled by W. W. Watts, '10 ft. above bottom? about 1490 ft. 11. ix. 95.' appears to be a Eurypteridean, possibly a leg fragment; it shows surface ornament which somewhat resembles that seen on the legs of *Carcinosoma punctatus* (Salter); a second fossiliferous Stutton specimen is B986, from 1500 ft., which is an internal cast of four chambers of an orthocone nautiloid.

"The two fossils found indicate that a Tremadoc or earlier age is unlikely and the Eurypterid evidence suggests that Ludlow or Downtonian age is more probable."

Harwich. Palaeozoic 1013 ft. below O.D. beneath Gault (Prestwich 1858; Jukes-Browne 1896; Whitaker 1877, 1916; Strahan 1913*a*, 1916).

Prestwich (1858) concluded that the "Black slaty rock" was Palaeozoic. The discovery of a large "Posidonia" satisfied most geologists that the rock was lower Carboniferous.

Eventually Watts (Jukes-Browne 1896) re-examined this specimen and showed it to be a rippled surface at an angle with the bedding. As a similar surface was found its organic origin was discredited. This same specimen (MI 7271) compares favourably with structures commonly seen in contemporaneously-disturbed mudstones. Other small material in the Sedgwick and Geological Survey Museums varies between banded mudstones with graded bedding and fissile cleaved mudstone. At 1096 and 1072 ft. the dip can be determined as about 45°.

Lowestoft. Palaeozoic 1615 ft. below O.D. beneath Lower Greensand (Whitaker 1906; Strahan 1913*a*, 1913*b*, 1916).

Strahan (1913*b*) describes small fragments of darkish or pale hard mudstone, micaceous in parts—not obviously cleaved.

There are about twenty-eight specimens in the Geological Survey Museum and Dr Stubblefield has re-examined these. He reports:

"There are some undoubted fragments of a small *Lingula* (Z. 277, 278, 293) and *Orbiculoidea* (Z. 279, 280, 294); less definite fragments of *Ceratiocaris*? and an unidentified fragment (Z. 297). ...This, along with other fragments, was submitted to Sir A. S. Woodward in 1912 and to Professor D. M. S. Watson in 1939 for opinions on any vertebrate remains present. Neither of these specialists would admit the presence of vertebrates.

"The presence of *Orbiculoidea* makes Cambrian age unlikely; from *a priori* reasoning, Ordovician is unlikely—the strata may therefore be Silurian; I am not prepared to name the brachiopods specifically from the material available."

Culford. Palaeozoic 527 ft. below O.D. beneath Lower Greensand (Whitaker 1894; Strahan 1913*a*, 1916).

Whitaker describes "a hard, light greenish grey slaty rock, showing what seems to be two sets of cleavage planes"; "fragments of argillite" with quartzose veins, and also imperfect slates (cf. Killas).

The three specimens in the Geological Survey Museum add nothing to this.

The London group

The area round London is pierced by a large number of bores. It is unfortunate that the dense population, which has led to the making of these bores, prevents seismic work being done in the same area.

Fobbing. Palaeozoic 1062 ft. below O.D. beneath Gault (Dewey, Pringle and Chatwin 1925).

The shales yielded fragments of *Acrotreta* of Cambrian type. They are compared lithologically with the Lingula Flags.

Sheerness. Palaeozoic 1341 ft. below O.D. beneath Lower Greensand (Lamplugh *et al.* 1923).

The percussion drill yielded small fragments only, from which an approximate upper boundary was fixed and the "dark blueish shale or slate" were correlated with the Silurian of Chilham and Bobbing.

Ware. Palaeozoic 686 ft. below O.D. beneath Gault (Hopkinson 1880; Etheridge 1881; Whitaker and Jukes-Browne 1894; Strahan 1913*a*, 1916; Whitaker 1921).

These rocks have always been described as Wenlock and are known to dip at about 40°. Stubblefield has recently re-examined the material at the Geological Survey and from a determination of about 30 genera and species concludes that the age of the strata from 800 to 827 ft. is "Wenlock; and probably all Wenlock shale—there is not sufficient evidence to state that the crystalline limestone specimen from 800 ft. represents the Wenlock limestone; a second limestone fragment is recorded from 820 ft. This lithological and faunal facies of Wenlock is also developed at Cliffe."

There are also similar cores at the Sedgwick Museum.

Cliffe. Palaeozoic 1025 ft. below O.D. beneath Lower Greensand (Whitaker 1908 *a*, *b*; Barrow and Wills 1913; Strahan 1913 *a*, 1916; Lamplugh *et al.* 1923).

Silurian has been described from this bore. The Geological Survey Museum has specimens from just below the Palaeozoic Floor and according to Stubblefield these comprise "*Atrypa reticularis*, *Leptelloidea* (*Leangella*) *segmentum* and crinoidal columns indicating Wenlock." These fossils are decalcified, indicating that the zone of subaerial denudation had not been altogether removed by marine erosion.

Little Missenden. Palaeozoic 741 ft. below O.D. (Strahan 1916; Whitaker 1921; Straw 1933).

Straw (1933) described the fauna in detail. It is extremely rich and unlike any other British assemblage.

The upper 29 ft. of *Beyrichia noetlingi* Beds compare with erratics in East Prussia which may be derived from the floor of the Baltic and also with the Stonehouse Formation of Nova Scotia. This probably indicates lowermost Devonian or Upper Downtonian, while the fish beds below are not earlier than late Downtonian.

Bushey. Palaeozoic 703 ft. below O.D. beneath Gault (Whitaker 1921; Edmunds and Stubblefield 1936).

This bore-hole, recorded with mistaken figures by Whitaker (1921), was deepened in 1934. Rocks assumed to be Devonian were struck at 899 ft. and were unfossiliferous till 979 ft. *Tentaculites* was found which makes a post-Devonian age unlikely and the facies is very similar to the basal 20 ft. of core at Little Missenden which is one of the nearest bores and penetrates Upper Downtonian or Lower Devonian.

Cheshunt (Turnford). Palaeozoic 870 ft. below O.D. beneath Gault (Hopkinson 1880; Etheridge 1879, 1881; Whitaker 1889, 1921; Whitaker and Jukes-Browne 1894; Strahan 1913 *a*, 1916).

Thirty feet of "hard dull purple shale" were identified by Etheridge as Devonian. He stated (1881) that the fauna included "*Spirifera disjuncta*, *Rhynchonella cuboides* and *Avicula damnoniensis*" and gave the age as Upper Devonian. Vaughan (1912) recorded that "the specimens labelled '*Spirifer disjunctus* Sow.'... might safely be labelled Upper Devonian or basal Carboniferous."

There are large fossiliferous slabs of the 15 in. core at both the Geological Survey Museum and the Sedgwick Museum. Stubblefield has examined the former which are better preserved and include a grey crystalline crinoidal limestone rich in *Tentaculites*. He was unable to confirm the records of *R. cuboides* and *A. damnoniensis* but to the record of many specimens of *Spirifer* (*Cyrtospirifer*) *verneuili* Murchison [olim *S. disjunctus*] he would add *Chonetes* (*Plicochonetes*) *margaritaceus* Whidborne, a species lately figured from the German Etroeungt beds. Concerning the age, he reports "Upper Devonian and probably as late as Etroeungt Beds." A final decision as to age is partly a question of terminology and the possibility of Lower Carboniferous is not excluded.

Tottenham Court Road (*Meux Brewery*). Palaeozoic 978 ft. below O.D. beneath Lower Greensand (Prestwich 1878; Whitaker 1872, 1889; Barrow and Wills 1913; Strahan 1913*a*, 1916; Buchan 1938).

Prestwich (1878) notes: "Mottled red, purple and light green shales, very finely micaceous and with well preserved fossils in places; dips at an angle of 35°; a few seams of red and grey quartzite." From the fauna these were classed as Upper Devonian.

The principal cores are in the Oxford University Museum, and additional specimens are in the Sedgwick Museum and the Geological Survey Museum.

Etheridge (Prestwich 1878) states that the Oxford cores contain *Spirifer disjunctus*, *Rynchonella cuboides*, *Edmondia*, *Orthis* and *Chonetes*. The Geological Survey Museum cores according to Stubblefield contain no *Sp. verneuili* [= *S. disjunctus*] nor *R. cuboides* but *Tentaculites*, *Camarotoechia* sp., *Chonetes*, cf. *laguessianus* (de Koninck), *Hustedia*?, cf. *Janeia laevigata* (Goldfuss), *Leiopteria*?, *Nuculana* sp., cf. *Prothyris contorta* are present.

Kentish Town. Palaeozoic 927 ft. below O.D. beneath Gault (Prestwich 1856, 1872, 1878; Whitaker 1889; Barrow and Wills 1913; Strahan 1913*a*, 1916; Buchan 1938).

"Hard micaceous, red and variegated fine-grained sandstones and clays" penetrated beneath the Gault were first taken as a fulfilment of Prestwich's prophecy that Lower Greensand would be found. Cretaceous fossils which fell down the bore hole also confused the issue. Being unfossiliferous it was later classified as Wealden, Triassic, Permian and finally Devonian by comparison with similar rocks near Mons. This Devonian classification was confirmed by the later London wells.

Southall. Palaeozoic 1040 ft. below O.D. beneath Gault (Proctor 1912; Barrow and Wills 1913; Strahan 1916; Buchan 1938).

Proctor (1912) describes red mottled clays and sandstones with occasional bands of grit. Mica is very abundant and the rocks show false bedding.

The rock is lithologically similar to that in the Kentish Town, Crossness and especially Richmond bore-holes.

Fish remains, identified by Sir A. S. Woodward, consist of scales and teeth of *Holoptychius* and plates of *Bothriolepis*—both characteristic Upper Devonian or Old Red Sandstone age.

The remaining bores in the London region which strike the Palaeozoic are also classified as Old Red Sandstone on lithological grounds. There are specimens from all these bores in the Survey Collection.

Beckton. Palaeozoic 963 ft. below O.D. beneath Gault (Barrow and Wills 1913; Strahan 1913*a*, 1916; Whitaker 1916; Buchan 1938).

Chiswick. Palaeozoic 1095 ft. below O.D. beneath Gault (Strahan 1913, 1916; Barrow and Wills 1913; Buchan 1938).

Crossness. Palaeozoic 1002 ft. below O.D. beneath Gault (Prestwich 1878; Whitaker 1889, 1908 *b*; Barrow and Wills 1913; Strahan 1913 *a*, 1916; Buchan 1938).

Richmond. Palaeozoic 1220 ft. below O.D. beneath Great Oolite (Judd 1884; Whitaker 1889; Strahan 1913 *a*, 1916; Arkell 1933; Buchan 1938).

Streatham Common. Palaeozoic 1010 ft. beneath Great Oolite (Whitaker 1889, Strahan 1913 *a*, 1916; Arkell 1933; Buchan 1938). Dr Stubblefield reports that the Geological Survey Museum specimen B 1028 from 1258 ft., i.e. 1148 ft. below O.D., appears to contain vertebrate fragments and in lithology resembles the Auchenaspis Grits of the Welsh Borderland Downtonian.

Willesden—Park Royal. Palaeozoic 1040 ft. below O.D. beneath Gault (Barrow and Wills 1913; Strahan 1913 *a*, 1916; Buchan 1938).

Willesden—Stonebridge Park. Palaeozoic 968 ft. below O.D. beneath Gault (Barrow and Wills 1913; Strahan 1913 *a*, 1916; Buchan 1938).

Western group

Gayton. Palaeozoic 417 ft. below O.D. Beneath Trias (Eunson 1884; Woodward 1909; Strahan 1913 *a*).

Eunson (1884) describes a littoral deposit of Carboniferous below the Trias and itself resting on Carboniferous Limestone. At 778 ft. there is a change to sandstones and coarse grits.

Kettering Road—Northampton. Palaeozoic 528 ft. below O.D. beneath Trias (Eunson 1884; Woodward 1909; Strahan 1913 *a*).

Eunson (1884) describes between 738 and 806 ft. crystalline conglomerates and sandstones lying unconformably on Carboniferous limestone from which blocks of dolomite have been derived and form the lowest bed. The Carboniferous limestone is crowded with characteristic Viséan fossils.

Orton. Igneous rock at 341 ft. below O.D. beneath Permo-Triassic (Eunson 1884; Woodward 1909; Strahan 1913 *a*; Bernard Smith 1936).

Bernard Smith (1936) writes: "Quartz-porphyrite or quartz-felsite with eroded surface. Distinct cleavage in the rock at an angle of 18° with the axis of the core." Similar rocks are found at Charnwood Forest where they are known to be Pre-Cambrian.

Great Oxendon. Igneous rock at 375 ft. below O.D. beneath Keuper (Bernard Smith 1936).

The Mesozoic rocks are of littoral type and rest on quartz-felsite, as at Orton.

Bletchley (*Fenny Stratford*). (Thompson 1890; Kendall 1905; Jukes-Browne 1889, 1895; Davies and Pringle 1913; Strahan 1913 *a*; Arkell 1933). This bore has been discussed above.

Calvert (*Charndon and Steeple Claydon*). Two bores close together reaching the Palaeozoic at 158 and 154 ft. below O.D. beneath Lower Lias (Davies and Pringle 1913; Strahan 1913 *a*, 1916; Whitaker 1921; Arkell 1933).

Steeply dipping shales with basaltic sills and a weathered surface are described. The faunas have been accurately determined and, with *Clonograptus*, indicate Tremadoc Shinetone shales (Upper Cambrian).

West of this group of bores the Carboniferous has been struck as at Brandon, Botsford and Burford where Coal Measures are penetrated.

The information given by all these bores about the nature of the Palaeozoic floor is summarized in figure 17 which also gives the velocities of elastic waves in the material underlying the floor. These velocities fall geographically into three groups (table 8). First, all the six stations north of lat. 52° 25′ give higher velocities than any of the stations to the south. The mean velocity is 18,090 ft./sec. Near Great Oxendon there is a bore which enters a felsite at 760 ft. The high velocity at this station is doubtless due to this rock and that at the neighbouring stations (Laxton, Benefield and Corby) is presumably also caused by the presence of an igneous rock. The high velocities at Feltwell and Bridgham farther to the east suggest that igneous rocks may extend along the northern edge of our area.

TABLE 8. VELOCITIES IN THE PALAEOZOIC ARRANGED IN GROUPS

Laxton	17,800	Leighton	15,360	Swaffham Prior	13,720
Benefield	18,040	Lakenheath	15,890	Madingley	13,400
Corby	18,670	Culford	16,640	Fulbourn	13,260
Feltwell	17,540	Kentford	16,170	Tempsford	13,860
Bridgham	19,600	Pertenhall	16,580	Houghton Conquest	12,810
Great Oxendon	16,960	Great Staughton	16,370	Bassingbourn	13,050
Mean	18,090	Bourn	14,420	Saffron Walden	13,200
		Mean	15,920	Arlesey	13,500
				Meesden	13,580
				Westmill	13,760
				Mean	13,420

South of this are two groups of stations, one with seven stations giving a mean velocity of 15,920 ft./sec., the other with 11 stations giving a mean of 13,420 ft./sec. The remaining three stations (Cambridge, Fenstanton and Bow Brickhill have low velocities but do not form a geographical group).

The result at Culford suggests that the 15,920 ft./sec. group is the lower Palaeozoic mudstones found in the bores there and elsewhere in Suffolk and Essex. The 13,420 ft./sec. group has not been met with when shooting in the immediate vicinity of any bore-hole, though that at Ware is only 8 miles to the south of the seismic station at Westmill; it is extremely probable that this velocity group represents a Palaeozoic sedimentary rock somewhat softer than the mudstones found in the other bores.

The bore-holes and seismic results therefore indicate an extensive area of lower Palaeozoic sedimentary rocks under east England. There is palaeontological evidence for Cambrian, Silurian and Devonian, and from the lithology, which includes slumped mudstones, it is probable that the rocks found in the bores near Harwich and at Culford are part of a thick series and that the area is crossed by a geosyncline. The northern

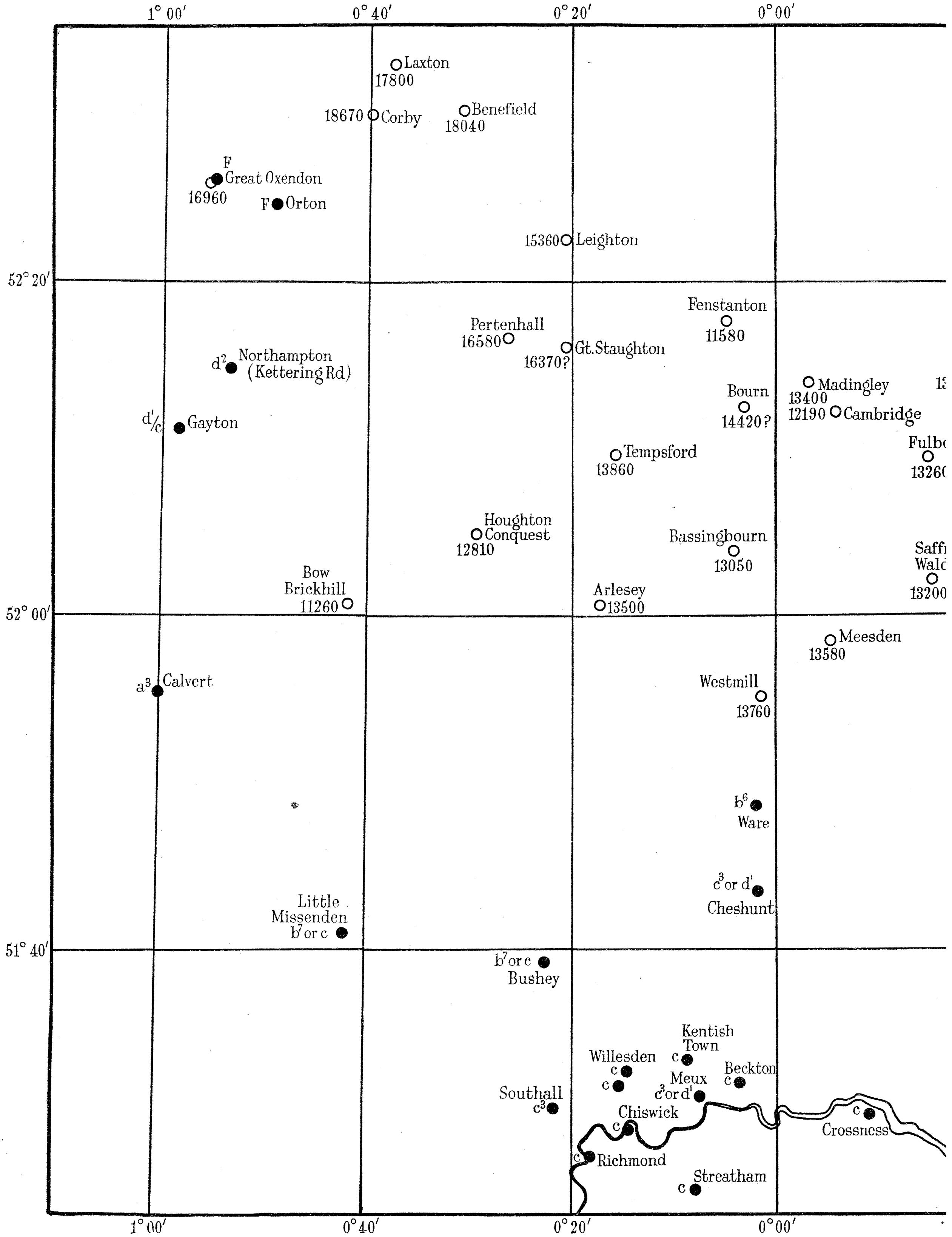


FIGURE 17. Nature of the Palaeozoic floor (1 in. = 10 miles, 1 : 633600). ○ = Seismic stati
by the Geological survey symbols (F = Felsite, a^{1-3} = Caml

nic stations with velocities of waves in ft./sec., ● = bore-holes reaching the Palaeozoic, the age is indicated = Cambrian, b^{4-7} = Silurian, c^{1-3} = Devonian and d^{1-5} = Carboniferous).

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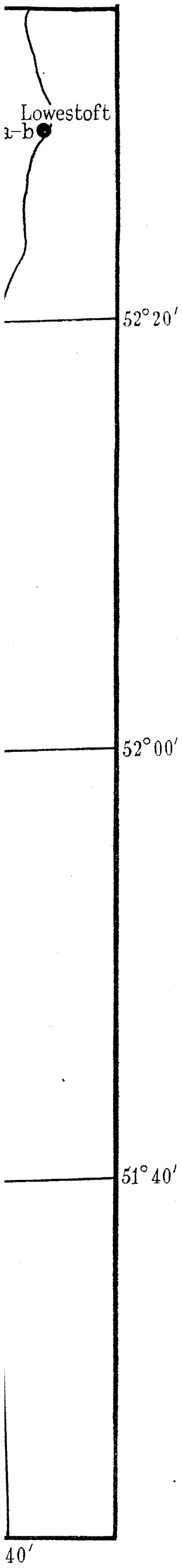

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boundary of this mass of sediments may be indicated by the sudden increase in velocity about latitude 52° 25′ but further stations are required to the north of this line. The southern boundary may be indicated by the occurrence of the shelly facies of the Silurian at Ware and Cliffe.

In order to determine the form of the geosyncline more precisely it will be necessary to find if the sediments giving velocities in the 13,420 ft./sec. group are similar to those at Ware or to those at Harwich and if possible to determine the direction of the dip. The latter might be possible from velocity measurements in different directions, but would probably require a bore-hole. At the Cheshunt and Ware bores the dip is reported to be to the South East but it is not known how this was determined nor if it is reliable.

We are indebted to numerous landowners for permission to make measurements on their land; during the whole of this work we have only once been refused permission to make the necessary explosions. Two of us (C. K.-G. and T. G.) are indebted to the Department of Scientific and Industrial Research for grants which have enabled us to take part in this work.

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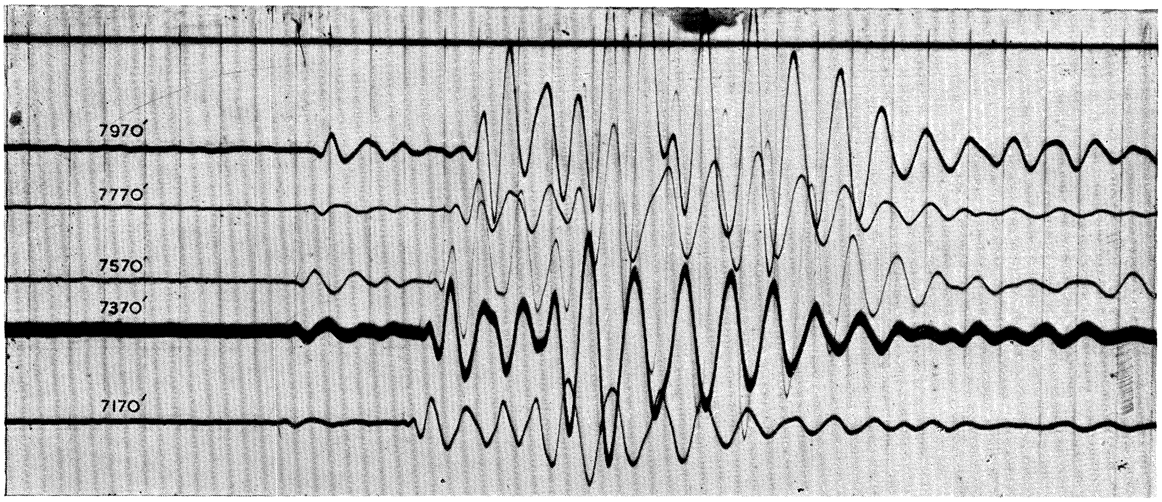


FIGURE 18. A record taken at Corby at 7170–7970 ft. from 15 lb. of gelignite. The interval between alternate time marks is 0·111 sec. The top trace is that on which the instant of explosion is recorded. The first wave to arrive is the refracted wave from the Palaeozoic (or at this station probably Pre-Cambrian) floor. It is followed by a well-marked direct wave. Reduced to 0·65 natural size.

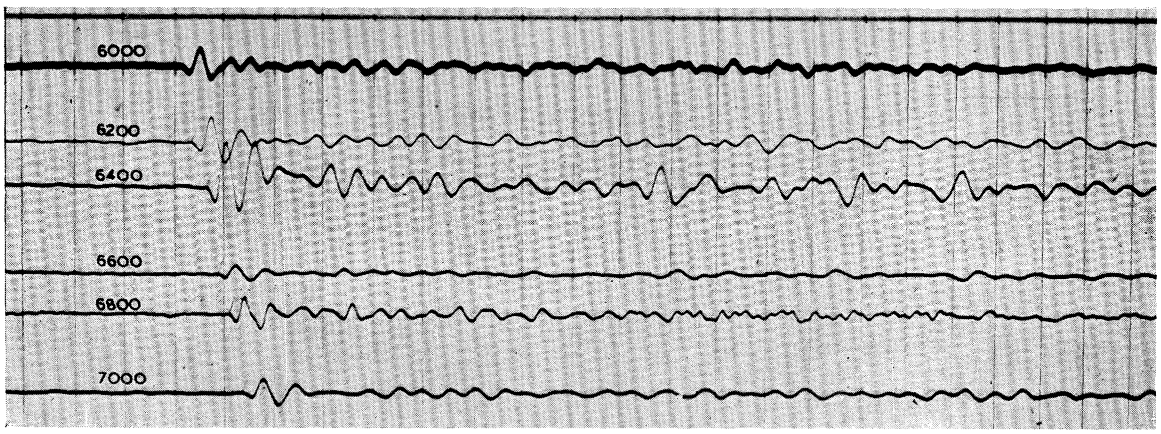


FIGURE 19. A record taken at Fulbourn at 6000–7000 ft. from $10\frac{1}{2}$ lb. of gelignite. The first wave to arrive is the refracted wave from the Palaeozoic floor. There is no direct wave in marked contrast to the preceding figure. This rapid attenuation of the direct wave is characteristic of chalk. Reduced to 0·65 natural size.

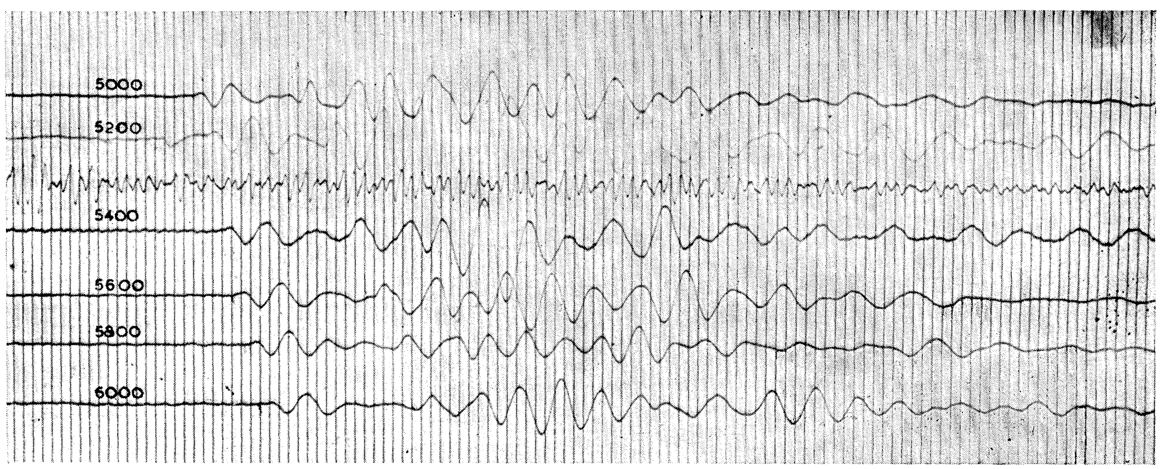


FIGURE 20. A record taken at Westmill at 5000–6000 ft. from 14 lb. of gelignite. The time marks are every 1/100 sec. The first wave to arrive is again the refracted wave and there is no direct wave visible. The third trace is that connected to the wireless recording the instant of explosion. Up to the instant of explosion (which occurs on the part of the record preceding that reproduced) the trace is steady; after the explosion it continues to vibrate as the wireless transmitter is shaken by the ground motion. Reduced to 0·65 natural size.

Figure 21. A record taken at Bridgham at 400–1400 ft. from $\frac{1}{2}$ lb. of gelignite. The first wave to arrive is the direct wave. The top trace shows the instant of explosion. The instruments were not all connected the same way round; if they were, the first kicks would all be in the same direction. Reduced to 0·8 natural size.

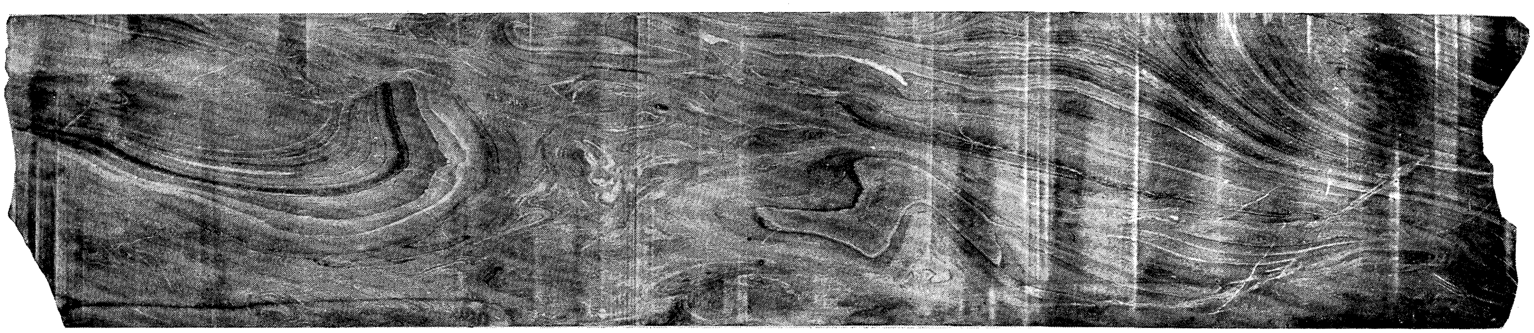


Figure 22. Section of a piece of core from the Weeley bore preserved in the Sedgwick Museum. This core shows remarkable structures which must have been formed while it was still plastic. The original is $4\frac{1}{2}$ in. wide. The transverse markings are saw cuts. The top of the core is on the left.

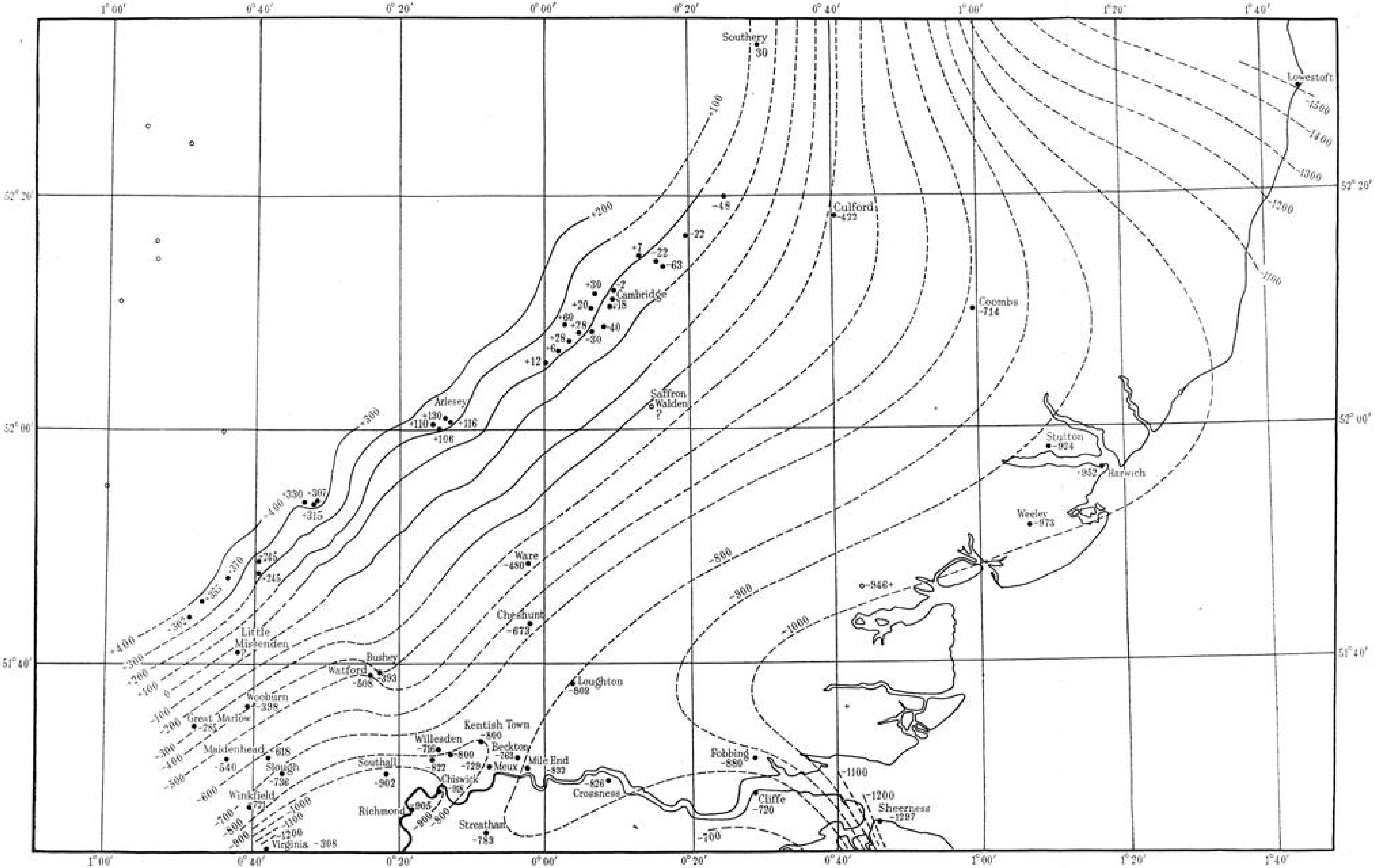


FIGURE 13. Contours of the base of the Chalk in feet above O.D. (1 in. = 10 miles, 1 : 633600). ● = bore-holes.

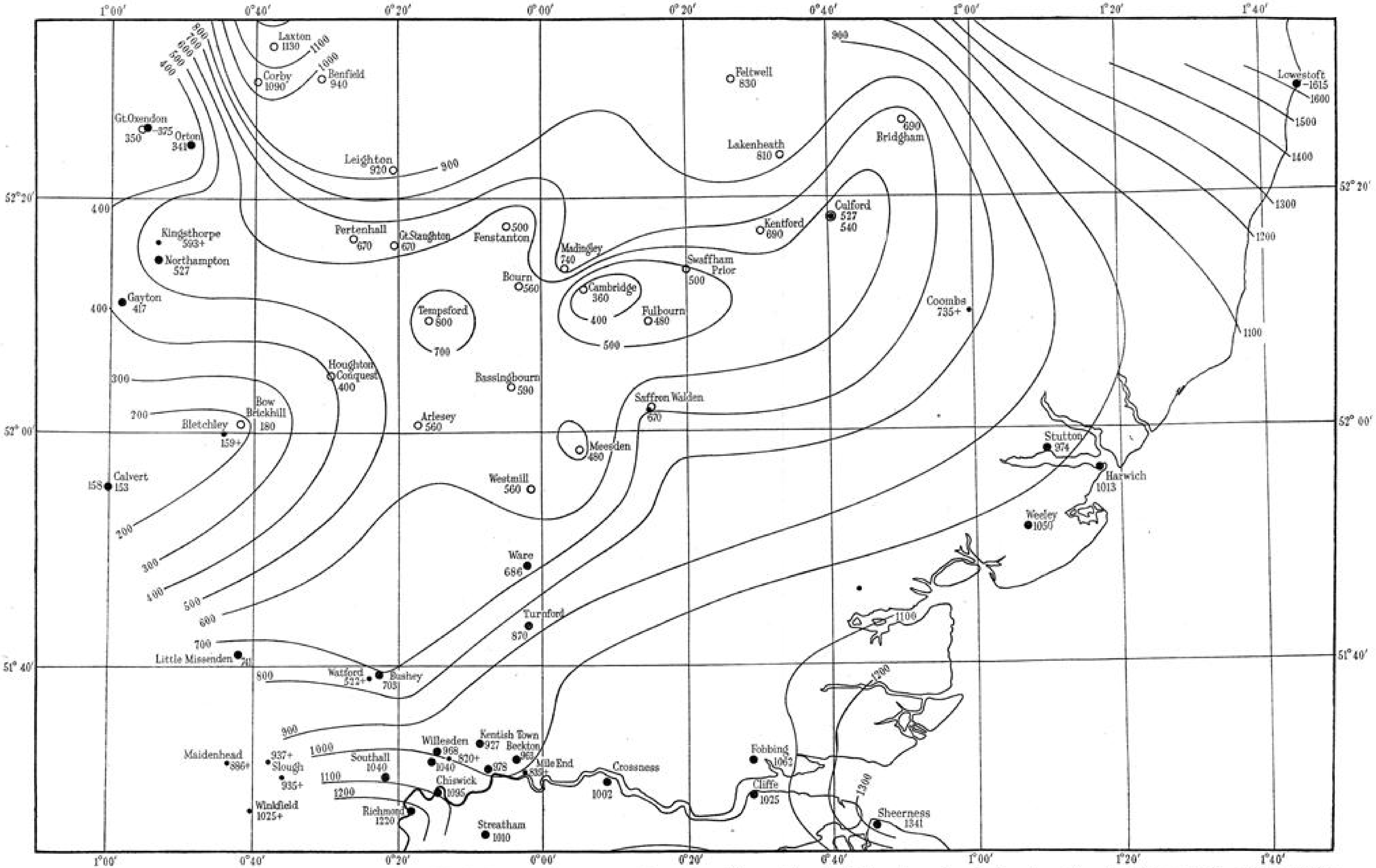
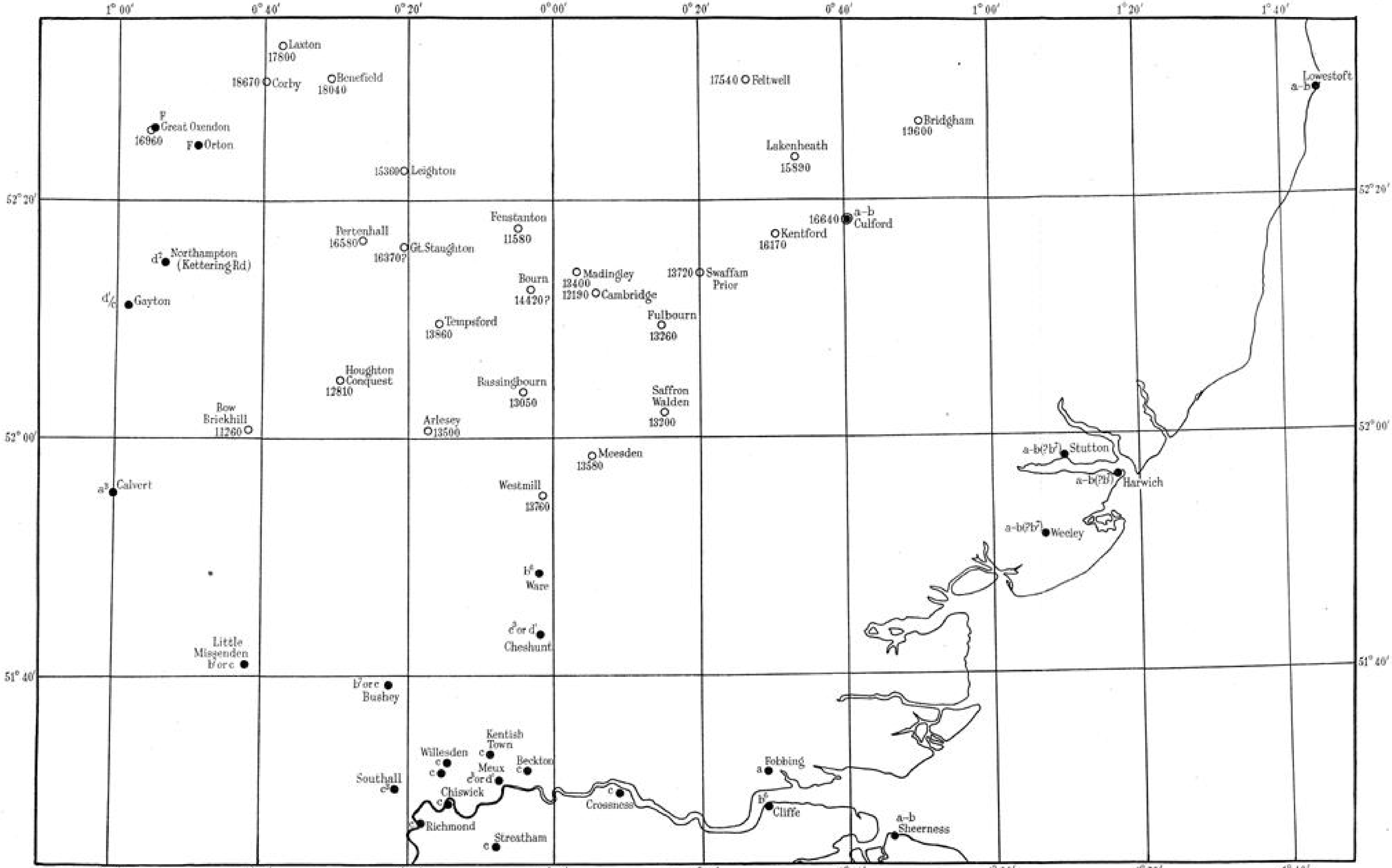


FIGURE 14. Contours of the Palaeozoic floor in feet below O.D. (1 in. = 10 miles, 1 : 633600). ● = bore-holes reaching the Palaeozoic, • = bore-holes not reaching the Palaeozoic, ○ = seismic stations.



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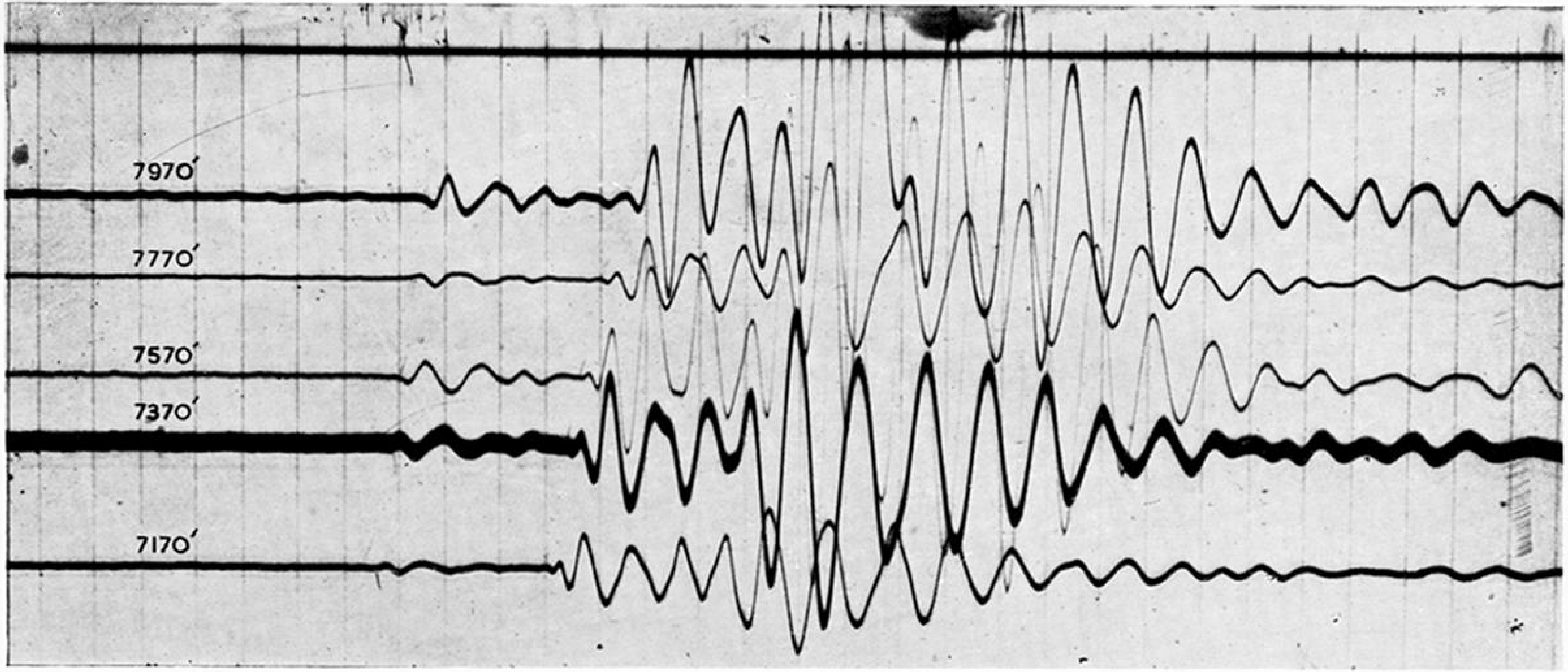

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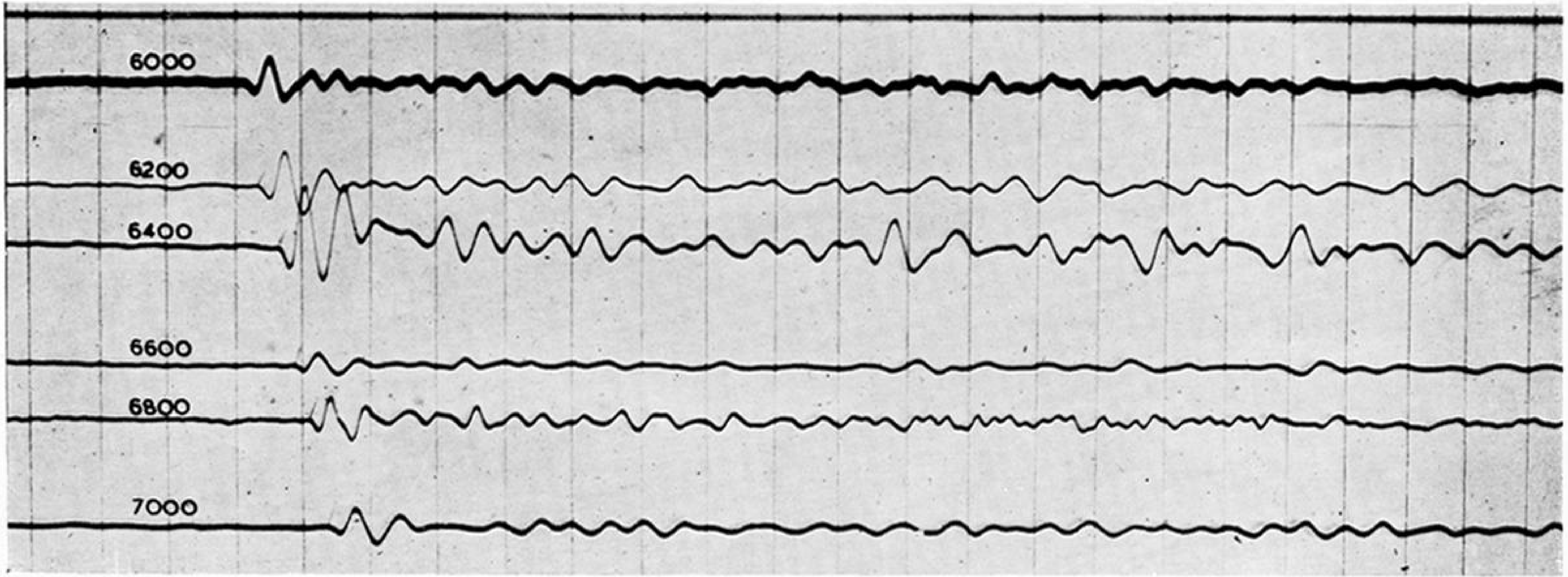

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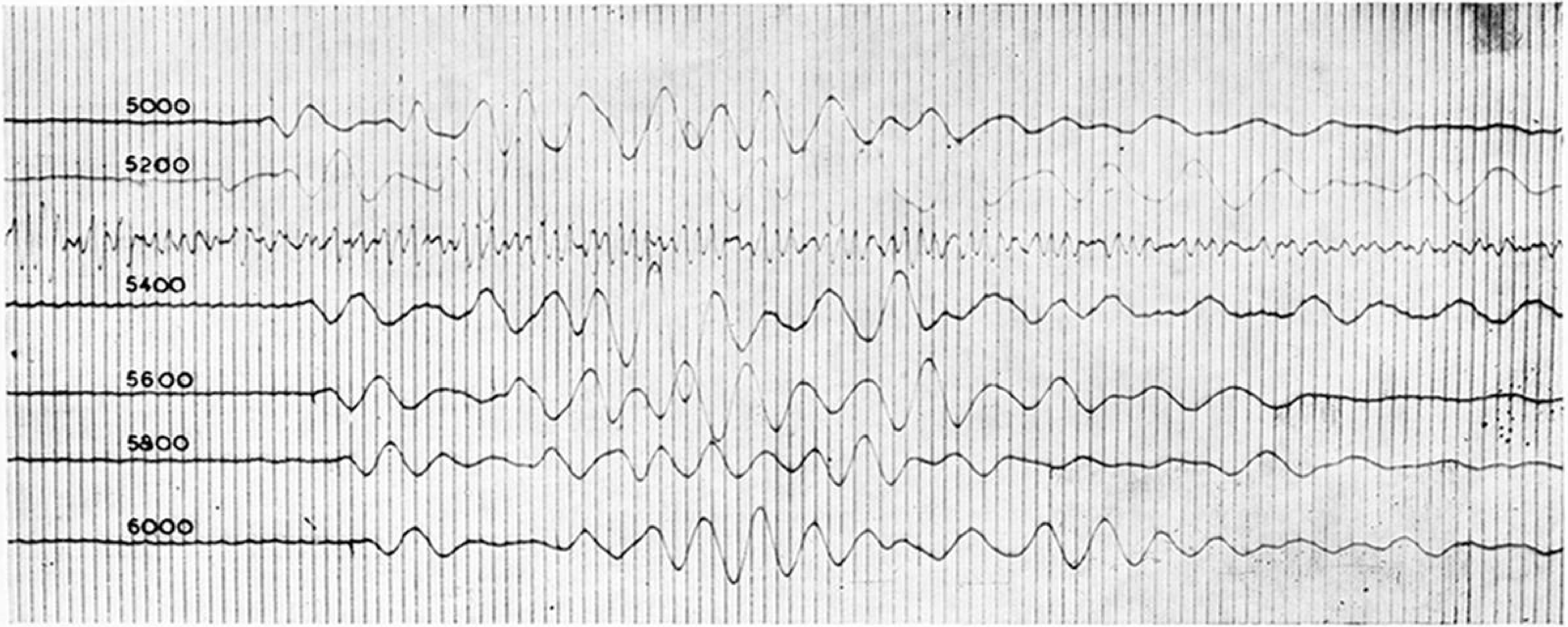

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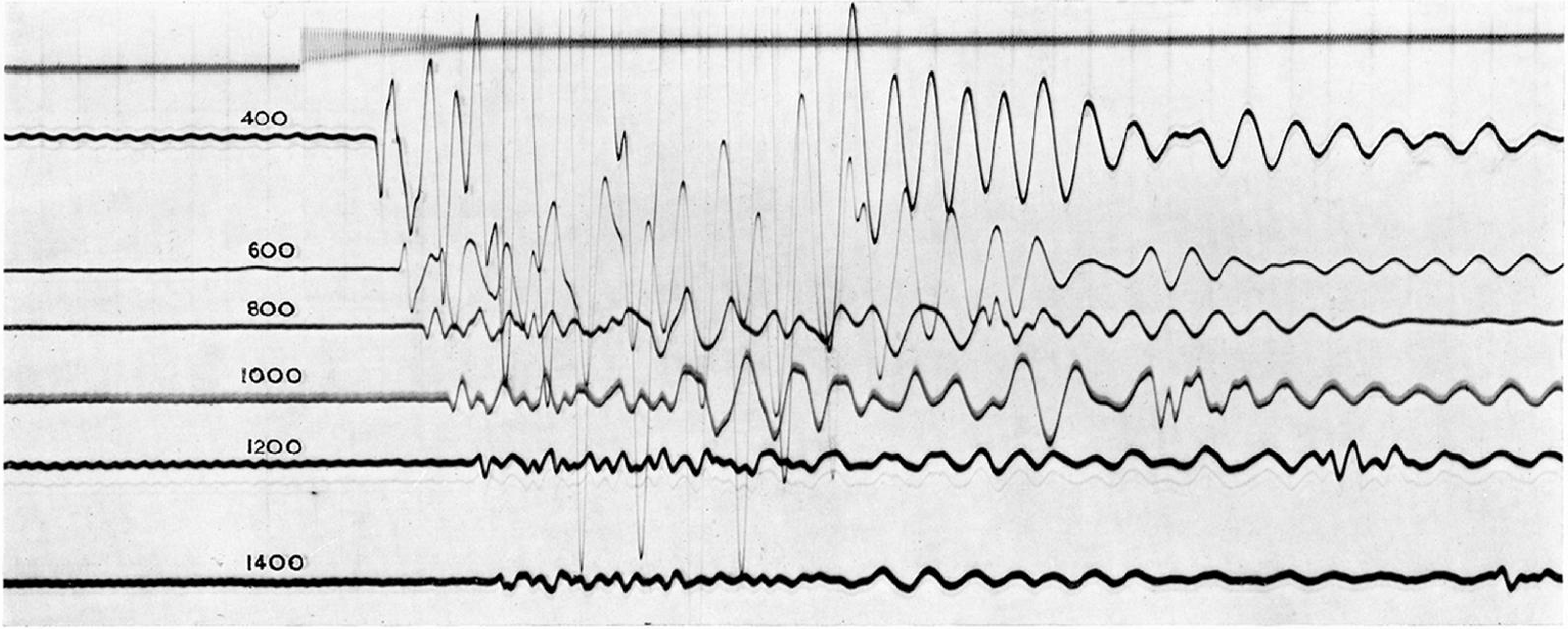

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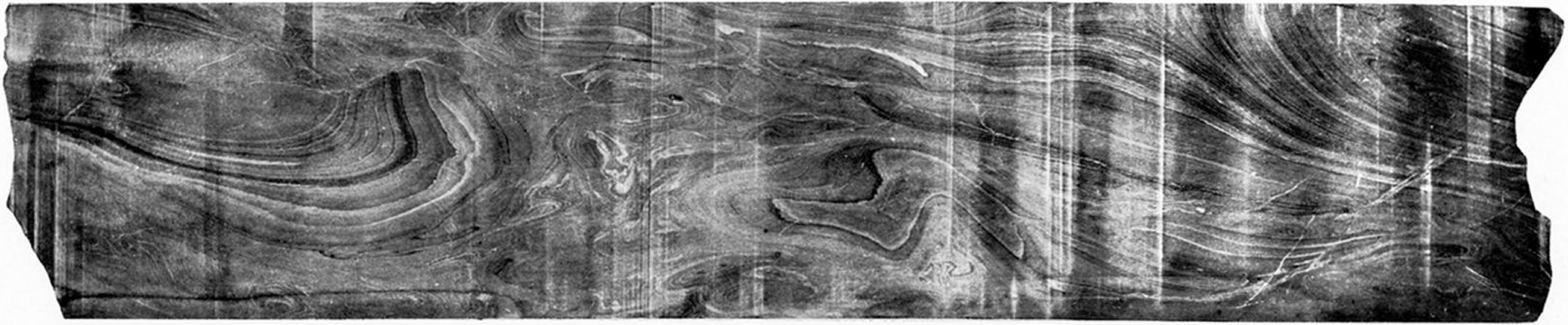

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