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Studies in Glacial Tectonics.

BY
GEORGE SLATER, D.Sc., D.I.C., A.R.C.S.

1. Glacial Tectonics as reflected in Disturbed Drift Deposits.
2. Studies in the Drift Deposits of South-West Suffolk.

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Reprinted from Proceedings of the Geologists' Association, Vol. XXXVII. (1926), pp. 392-400; and Vol. XXXVIII. (1927), pp. 157-216.

LONDON :
EDWARD STANFORD LTD.,
12, 13, & 14, LONG ACRE, W.C.2.

Issued December, 1927.

Price 1s. 6d.

GLACIAL TECTONICS AS REFLECTED IN DISTURBED DRIFT DEPOSITS.*

BY GEORGE SLATER, D.Sc., D.I.C., A.R.C.S.

PART I.

PRELIMINARY CONSIDERATIONS.

I. FOREWORD.

THE study of glacial phenomena, both past and present, is one of considerable difficulty. In spite of the combined labours of a host of workers for over a century, including some of the most eminent geologists and physicists of the day, the subject still bristles with difficulties. No other branch of geology, perhaps, has been so provocative of controversy, or has led to the expression of so many diverse views.

In other branches of science the labours of the early pioneers revealed fundamental principles which formed a solid foundation for all future work. In glaciology, although this is also true to a certain extent, we appear to be still groping for some of the fundamental truths underlying the subject.

Glaciology in its widest sense, *i.e.*, including the study of drift deposits, has not yet reached the dignity of an independent branch of "Geo-Physics."

Stages in the development of all sciences have usually been marked by the initiation of new methods of exact treatment, which were followed by periods of rapid development, resulting in new conceptions of the cause of the phenomena.

The brief resumé of the evolution of the study of glaciology which follows is sufficient to show that we have now reached the stage in the study of disturbed drift deposits when exact treatment is necessary; the following papers suggest that the collection of measured data in such sections explains much that has hitherto been obscure, and yields information which may, in the future, lead to the foundation of a new branch of Geo-Physics, by the combined labours of geologists in the field and physicists in the laboratory.

II. INTRODUCTION.

HISTORICAL RETROSPECT. FOUR LANDMARKS IN THE EVOLUTION OF THE STUDY OF GLACIOLOGY.

The history of the investigation of glacial phenomena falls naturally into four periods.

a. First period (1750-1840).

During the first half of the 19th century an enthusiastic body of European workers paid great attention to the phenomena

* Part I, of Thesis approved for the Degree of Doctor of Science in the University of London.

of Alpine glaciers and the evidences of greater glaciation in former epochs. Amongst these early pioneers the names of Venetz, Charpentier, Agassiz, Carl Vogt, and Saussure stand pre-eminent :

b. Second Period (1840-1890).

The enthusiasm of Agassiz attracted the attention of physicists, whilst the analogy which he pointed out in 1840 between the glacial phenomena of the Alps, and the drift deposits of the mountainous parts of Great Britain, attracted the attention of geologists. This led to the differentiation of the problems, in the middle part of the century, along two distinct lines.

- (a) The investigation of the movement and physics of ice-action commenced in 1840. James Forbes in 1842-44 investigated the movement of glaciers and formed his theory of the plasticity of ice, whilst at a later period (between the years 1849-57) Faraday, Tyndall, and other leading physicists of the day, investigated the physics of ice experimentally.
- (b) Between the years 1848 and 1860 Ramsay confirmed the analogy of Agassiz and described the glacial phenomena of North Wales.* This led to an important development of the subject, as detailed mapping of drift deposits ultimately became an integral part of the work of the Geological Survey, as well as the recognised method of drift research by individual workers.

The second period was, therefore, one of great progress in the accumulation of facts, but it was unfortunately marred by a growing tendency to formulate theories prematurely. This tendency was largely due to the increased difficulty which was experienced in explaining the facts obtained by mapping by reference to Alpine phenomena, for the analogy already mentioned was found to be incapable of application to the drift deposits of lowland areas.

The chief points of discrepancy were as follows :

- (a) In the Alps the structural unit is the surface moraine which occurs in the form of lines or crescentic mounds.
- (b) In lowland areas the structural unit is the deposit of Boulder Clay which occurs in sheets.
- (c) The over-emphasis of floating ice as a geological agent, owing to the influence of the growing popularity of polar exploration.

During the latter half of this period there was an increasing lack of co-operation between geologists and physicists. The latter devoted their attention largely to the phenomena of pure ice, hence their intricate and exact results appeared to have little application to the problems met with by field-workers. As a result, geological theory increasingly lagged behind the accumulation of facts.

One of the greatest difficulties of the field-workers in correlating drift deposits was the fact that the mapping was entirely based on the lithology of the beds, as fossils when found were

* The Old Glaciers of Switzerland and North Wales, 1860.

frequently derived. In this respect the complicated drift deposits of Norfolk constituted one of the most difficult areas in England. Nevertheless, by the close of this period, inferences from observed facts led to many well-founded conclusions. Amongst these conclusions the following are important :

- (1) The source of the drift material was traced by means of erratics and boulders.
- (2) It was proved that the origin of the drift deposits was due to a large extent to land-ice.
- (3) The direction of movement of the ice was inferred.
- (4) The alteration in the physical geography of the country due to glacial action was described in many admirable papers.
- (5) The probable thickness and extent of the ice became well known.

c. Third period (1890-1900).

The third period belongs to the last ten years of the 19th century. During this period the investigations of American workers brought to light new phenomena of glaciers characteristic of Polar regions. These geologists focussed attention on the great importance of englacial material in Greenland glaciers as a structural unit, and the comparative insignificance of the surface moraines. The observations and deductions of R. S. Tarr, T. C. Chamberlin, W. Upham, W. O. Crosby, and R. D. Salisbury have proved an inspiration to other workers. The fundamental importance of englacial material to workers in Pleistocene drift deposits is indicated as follows :

- (1) Englacial material occurs as sheets or layers.
- (2) When melted out *in situ* it forms, amongst other materials, deposits of Boulder Clay.
- (3) When ice meets with an obstruction the ice as registered by the englacial material assumes definite tectonic structures.

Phenomena similar to those of the Greenland glaciers were described by Professors E. J. Garwood and J. W. Gregory, in a paper on Spitsbergen glaciers in 1898.

d. Fourth period (20th century).

i. Resumé of the Study, 1900-1925.

The first quarter of the 20th century may be described as a transition period during which the application of the new ideas derived from the study of Polar ice to that of Drift deposits is, to a very large extent, still in its initial stages. Hardly any analogies, either local or regional, have been made between the two, with the exception of H. B. Woodward's paper on the disturbances of the Chalk at Royston in Hertfordshire, 1903, and G. W. Lamplugh's description of the formation of Boulder Clay at Cora Island, Spitsbergen, in 1910. On the other hand the baffling difficulties met with in the endeavour to explain drift disturbances from other points of view is admirably illustrated in the paper by T. G. Bonney on the Møen and Rügen areas in 1899, in his controversy on the Trimmingham Chalk in

1905-6, and his paper on Royston refuting Woodward's explanation of the structure, as well as in his presidential address to the British Association in 1910. Again, in 1907, Sir H. H. Howorth expressed the view, in reference to the Norfolk disturbances, that "no section, however carefully drawn, is of more than ephemeral interest."

How false and mischievous is such an opinion may be gathered from the results obtained by the recording of serial sections, presented in this thesis. The recording of sections of a similar type at Chesham was carried out by Mr. G. Barrow in 1915.

The reasons for the slow progress of the subject appear to the author to be as follows:—

- (1) Absence of detailed work and the lack of accurate measurement of disturbed sections. T. G. Bonney's papers are all illustrated by diagrammatic free-hand sketches. The Survey sections of the Cromer coast, although admirable at the time when produced, are on a scale inadequate to illustrate the detailed structure.
- (2) The view that portions of disturbed outcrops of such formations as the Chalk had been moved *en masse* by the enormous pressure of an advancing ice-sheet.
- (3) The difficulties of obtaining exact stratigraphical criteria in the working out of drift deposits, such as fossil evidence. Incidentally, the modern methods of sedimentary petrology are of little value on account of the mixed assemblage of heavy minerals.
- (4) The endless controversies of the past had brought the subject into disrepute. A recent controversy over the succession of deposits at Leighton Buzzard shows that harmonised agreement has not yet been reached.

Even the disturbances themselves are not yet generally accepted as due to glacial action. For example, Professor John A. Allan, of the University of Alberta, Edmonton, in a letter to me, does not agree that the disturbed deposits of the Mud Buttes (see Part VII. of Thesis) are due to glacial action, but believes they are due to orogenic movements from the Rockies at the close of the Cretaceous period. During my recent investigation of the magnificent sections of Møens Klint, my friend, Mr. V. Hintze (who has studied the area for 30 years), gave me his considered opinion that the structure was due to post-Glacial earth-movements. The classic sections at Lønstrup in North Denmark have also been recently investigated by me in company with State-Geologist Mr. Axel Jessen, who made it clear that at present there is no settled opinion amongst Danish geologists as to the genesis of the structure. I was also informed by Danish friends that the opinion of some German geologists was that the disturbances seen in the island of Rügen were tectonic and due to earth-movements.

This short resumé is sufficient to show how great is the need for detailed work, and how little is known as yet on the subject of the glacial tectonics of disturbed drift deposits. The papers

submitted set out evidence which, it is claimed, proves that the principles of glacial tectonics may be recognised in all the sections described.

2. A new conception of disturbed drift deposits.

A few words are necessary at this stage to explain how the growth of the ideas underlying the present investigation took place. The method of accurate measurement was suggested in 1900 by the exposure of a magnificent section in the railway cutting one mile north-west of Ipswich station. The result of drawing this section to scale convinced me of the soundness of this method. The careful recording of all sections ultimately had its own reward, as the serial sections produced obviated the errors of exaggeration, and clearly demonstrated the tectonic structure of the deposits.

This slow development of the investigation extending over a period of 25 years ultimately led me to adopt a new conception of disturbed glacial deposits. This is as follows:

- (1) Glacial tectonics are reflected in disturbed drift deposits.
- (2) The disturbed material is regarded as having been englacial material which assumed definite tectonic structures when in the ice.
- (3) This structure has been preserved, and the beds have maintained their relative positions owing to an extremely slow rate of melting of interstitial ice aided by the blanketing of the whole by Boulder Clay.
- (4) Hence such deposits may be regarded as glacial-pseudomorphs, or, more graphically, to use the expression of the late Professor Grenville Cole, the beds represent a "Fossil Glacier," the "hard-parts" only being preserved.

This aspect of the subject leads to two important deductions (A. and B.)

- A. "Englacial material is analogous to the coloured material used by physicists to demonstrate in experimental physics the flow of viscous bodies." (Prof. A. N. Whitehead, F.R.S.).
"Hence the measured data of disturbed sections by the geologist will be suggestive for experimental lines of investigation by the physicist." (Prof. H. Levy, D.Sc.).
- B. Glacial deposits may be differentiated into two main classes, primary and secondary:
 - (a) *Primary glacial deposits.*
To this class belong various kinds of lithological material which have been deposited from ice without rearrangement by the agency of running water, such as Boulder Clays and loams, characterised by an anomalous lithology, disturbed material derived from local outcrops, and lentils of sand and gravel. These deposits contribute to the formation of drumlins under special conditions, and also to widespread deposits of drift. Under the influence of pressure, structure is developed, especially in the lower parts of the deposits. The present investigation is confined to deposits of this class. This type of deposit is the quarry for material which would provide the data of a branch of Geo-Physics.

(b) *Secondary glacial deposits.*

Deposits due to ablation.

To the second class belong all glacial deposits which have been melted out of ice and re-arranged, and sometimes re-deposited by the agency of running water. Sands and gravels showing cross-bedded structure, and laminated clays and loams are the chief types of such deposits. Hence all original structure of such deposits when in the ice has been totally destroyed. Topographical features formed by these deposits include moraines and eskers.

Most of the literature on drift deposits deals largely with deposits of this type (b).

The mapping of drift deposits brings out the fact that there is a topographical relationship between the two types of deposits (a) and (b), widespread deposits of Boulder Clay occurring between chains of moraines. This rhythmic alternation of the two is an index of periodic climatic variation. I have shown elsewhere* that the marginal melting of a glacial bears a direct relationship to the air temperature during the deglaciation of an area. Hence this branch of the subject is directly connected with the sciences of meteorology and geomorphology.

The two classes of deposits (a) and (b) are formed as a natural consequence of the melting of the ice in two directions: (1) downwards over the whole area of the glacier, and (2) the melting backwards of the ice along its margin. The size of the marginal moraine is an index of the relative interplay between precipitation and rate of melting.

III. GENERAL QUESTIONS INVOLVED.

(a) Superficial nature of the disturbances.

Disturbances attributed to glacial action have often been noted and occasionally described, the coast sections of Norfolk, for example, having long been classic ground for such phenomena. In that locality they are on an unusually large scale and of much complexity, rivalling those of Møen and Rügen. As a rule, however, sections are on a much smaller scale, and only show a portion of the structure; nevertheless, in all cases disturbances of this nature are marked by the following characteristics:

- (1) They are of local occurrence.
- (2) They are essentially superficial and in no way connected with disturbances due to earth-movements.

(b) Types of deposits in disturbed sections.

The most instructive sections of glacial disturbances in this country are those which occur in the east of England, north of the Thames, and south of the Wash, near the outcrops of the softer Mesozoic and Tertiary formations, portions of these

* Observations on the Nordenskiöld and neighbouring glaciers of Spitsbergen, 1921. *Journal of Geology*, vol. xxxiii., No. 4, May—June, 1925.

beds having been incorporated in the disturbances. The position and extent of disturbances in this area have been determined by the following factors:

- (a) The pre-glacial topography.
- (b) The physical properties of the geological formations composing the pre-glacial floor.

The disturbed material in such sections consists largely of material derived from one or more local geological outcrops.

If an outcrop is thick, as in the case of the chalk escarpment, the disturbed beds consist largely of that material; if, on the other hand, there are several comparatively thin outcrops of beds of various types of lithology, portions of each of these beds become incorporated in the disturbances. In addition to these locally derived beds, an upper series of glacial material may, or may not, occur, consisting of Boulder Clay and sands and gravels mostly of non-local origin.

In the absence of the latter series, locally disturbed beds if only exposed in incomplete sections are very misleading and may easily be mistaken for beds *in situ*.

The phenomena of the glacial action on the country rock underlying the disturbed beds will be dealt with at a later stage, as the composition of the floor of the glacier has an important bearing on the initiation of tectonic structure.

(c) Tectonics of disturbed drift deposits.

The fact that disturbed drift deposits are not fortuitous disturbances, but assume a definite tectonic structure, has been pointed out by three writers:

- (1) Clement Reid, in 1882, who described the structure of the Trimmingham Chalk and other parts of the Norfolk Coast.
- (2) H. B. Woodward, in 1903, who introduced the idea of thrust planes, in the shattered disturbed chalk at Royston.
- (3) George Barrow, in 1915, who described glide planes in the disturbances at Chesham.*

In each of these three areas, the disturbances are dominantly exposed on the "iceward side of the outcrop," hence only one aspect of the structure was described.

Again, in two of the areas, the disturbances have mainly affected the chalk-outcrop, a rock which from its homogeneous character does not lend itself readily to the detailed preservation of the structure. The structure in the disturbed chalk in these areas is mainly shown by anomalous dips, portions of folds and shattered bands of flints along thrust planes.

In the third example the material is eminently suitable for the preservation of structure, and the sections when described showed the thrust planes developed quite admirably.

* Excursion to Cowcroft Brickfield, Chesham, July 10th, 1915, *Proc. Geol. Assoc.*, vol. xxvi., Part 5, p. 330, 1915.

In some of the sections described in this thesis the whole of the structure was exposed of beds of considerable lithological variety, thus enabling the genesis of the structure to be followed in detail.

(d) **Theory of the Structure.**

Two hypotheses have been advanced in explanation of the structure in disturbed glacial deposits, the one based on deductions drawn from detailed work on actual exposures in Drift deposits, the other influenced by observations on modern Arctic glaciers. These hypotheses are as follows:—

- (1) Clement Reid came to the conclusion that the disturbances seen on the Norfolk Cliffs were due to the impact of a body of drift-laden ice against a local outcrop of chalk, the pressure of the ice forming folds in the rock analogous to the crumpling of a table-cloth by the hand.
- (2) H. B. Woodward, on the other hand, influenced by the work of American writers on Greenland glaciers, regarded the disturbed chalk of Royston as having been incorporated in the lower portion of a body of ice as englacial material which, after some amount of transportation, has been deposited in the positions now found.*

The present investigation proves that the former hypothesis is more especially true in the earlier phases of the disturbances, if applied to the movement of separate lenticles, and that resistance to friction by the country rock has resulted in the formation of a "core" or "nucleus" of definite form, resembling the *roche-moutonnée*. The latter hypothesis will be shown to be generally applicable to the subsequent disturbances, pressure especially, on the exposed sides of the "cores," taking the form of thrust planes, and squeezed anticlines, in association with the transported beds, which were moulded over the "cores."

Both hypotheses are, therefore, true within the limits prescribed above, yet neither is adequate in itself to explain the whole structure.

Regarded separately the two theories also involve different geographical conceptions, for, whilst the former presupposes a topographical feature which has been to some extent degraded, the latter postulates a topographical feature which has been accentuated by deposition of glacial material.

IV. GEOGRAPHICAL AREAS WHICH HAVE BEEN INVESTIGATED AND GENERAL SCOPE OF WORK (1926).

The complete series of sections described occurred in the following areas:—

A. ENGLAND:—

- Part II. South-West Suffolk; The Gipping Valley between Claydon and Ipswich.
- Part III. South-West Suffolk; The Hadleigh Road area, Ipswich.

* On some disturbances in the Chalk near Royston (Hertfordshire). By Horace B. Woodward, *Quar. Journ. Geol. Soc.*, vol. lix., Part 3, No. 235, pp. 362-374.

- Part IV. Cheshire; "Glacial observations in the neighbourhood of Wallasey." *Liv. Geol. Soc.*, vol. xiv., Part ii., 1925.
- Norfolk; Whitsuntide Excursion to the Cromer and Norwich Districts, *Proc. Geol. Assoc.*, vol. xxxiv., Page 223, 1923.
- D. Spitsbergen; Observations on the Nordens Kiöld and Neighbouring Glaciers of Spitsbergen, 1921. *Journal of Geology*, vol. xxxiii., No. 4, May-June, 1925.
- B. AMERICA:—
- Part V. United States of America, New York State; "The structure of the Drumlins on the southern coast of Lake Ontario." (Accepted for publication by the New York State Museum.)
- Part VI. Canada, Toronto; "A new section in the upper drift deposits of Toronto."
- Part VII. Canada, Alberta; "The structure of the Tit Hills, and Mud Buttes of Alberta." (Offered for presentation to the *Geol. Soc. of America*.)
- C. DENMARK:—
- Part VIII. The Island of Møen; "The disturbed Chalk and Drift deposits of Møen's Klint."
- Part IX. North Jutland; "The coast sections near Lønstrup." (Offered for publication to the Royal Society of Edinburgh.)

***STUDIES IN THE DRIFT DEPOSITS OF THE
SOUTH-WESTERN PART OF SUFFOLK.**

**PART I.—THE STRUCTURE OF THE DISTURBED
DEPOSITS IN THE LOWER PART OF THE GIPPING
VALLEY NEAR IPSWICH.**

By G. SLATER, D.Sc., D.I.C., A.R.C.S.

[*Read January 7th, 1927.*]

I. Introduction.

i. Location of Area.

THE sections to be described were excavated in the neighbourhood of Ipswich, Suffolk, and in the lower part of the Gipping Valley between Claydon and Ipswich, a distance of about 4 miles. With the exception of a large chalk pit at Claydon, all these excavations have been opened up since the completion of the Geological Survey of the district, and since the year 1900. The recording of the observations took the form of serial sections. Those of especial importance were confined to four special areas, which are as follows:—

- (1) The chalk pit of Messrs. Mason and Co., about 1 mile west of the village of Claydon.
- (2) The large chalk pit at Claydon situated on the outskirts of the southern end of the village about 3 miles north-west of Ipswich.
- (3) The brickyard of Messrs. A. Bolton and Co., 1 mile north of Christchurch Park, Ipswich, and between the Henley and Norwich Roads.
- (4) The sand pit of Messrs. A. Bolton and Co., which adjoins the brickyard, and lies west of the Henley Road.

The sections in the district referred to as "The Hadleigh Road Area, Ipswich," are treated separately in Part II.

The features that are revealed by the sections in this paper are in each case dominantly confined to one geological formation, whereas, on the other hand, those in the Hadleigh Road Area embrace features due to the incorporation of beds from five geological formations. Hence the series of sections in the upper part of the Gipping Valley furnishes an analysis of the more complicated types of structure seen in the Hadleigh Road Area. Comparison with phenomena exhibited by modern Arctic glaciers is therefore deferred until Part II, p. 183.

* Part II. of Thesis approved for the Degree of Doctor of Science in the University of London, 1926.

ii. Topography of the Gipping Valley.

The topography of the Gipping Valley is shown in the coloured Map (3). From this map it will be seen that the country is generally below the 200-foot contour between Claydon and Ipswich. Cross-sections at Claydon and Ipswich prove that the valley is of a broad trough-like form, characteristic of mature river development, whilst borings prove the deepening of portions of the central part owing to the formation of a glacial channel. The form of the valley is in striking contrast to those of the deep U-shaped valleys of the Alps (3 p. 614).*

Influence of the pre-glacial topography on the positions of disturbed areas.

The topography of the Hadleigh Road area suggested to the writer that the positions of disturbed areas bore some relationship to the contour of the sides of the valley, whether concave or convex. Subsequent detailed mapping by P. G. H. Boswell brought out the fact that disturbed areas were invariably situated on projecting spurs on the sides of the valley. The detailed sections to be described prove that, whilst these spurs are composed of outcrops of solid geological formations, the latter have formed nuclei for the formation of disturbed deposits, resulting in the formation of topographical features by glacial action.

The arrows marked on the map indicate the position of particular instances of disturbed areas. Hence such areas are local and the disturbances superficial. This view is supported by the evidence of well-sections to be dealt with at a later stage.

iii. Method of Work.

The present investigation rests almost entirely on field evidence. The methods of the petrology of sedimentary rocks have in one case been used to confirm the field evidence that the basal Reading Sands of the Hadleigh Road area were *in situ* and uncontaminated by glacial material. The majority of the sections in this area were drawn to scale and their positions marked on a large plan of the area (scale 1/500). Other exposures were photographed and "keyed" on the spot. A special topographical map on a scale of 50 feet to the inch was used for the construction of the geological ground-plan. This map was divided into 100-foot squares corresponding to similar squares pegged out in the area. Each square was then systematically examined, and the outcrops measured with a tape. Hence the map and sections together give a quantitative estimate of some of the disturbed deposits. Palæontological evidence was obtained from the Crag, where the fossils indicated a typical Newbournian fauna, and from boulders in the Chalky-Kimmeridgic Boulder Clay. The latter proved that material

See list references on p. 182.

had been derived from various Jurassic horizons, but that the bulk of the matrix of this clay had been derived from the outcrop of the Kimmeridge Clay.

The same method of recording the facts by means of detailed scale sections was adopted for other exposures, which have been repeatedly visited during the past 25 years. It is unfortunate that so many of these sections were only exposed for a brief period, as owing to the nature of the material, they were of striking beauty when freshly excavated. In other cases the positions of the sections were marked on the 25-inch ordnance map.

The mapping of the district on the six-inch scale was completed in order to determine the levels *in situ* of the geological formations incorporated in the disturbances. More precise information of the height above O.D. of wells, and of the subface and superface of certain well-marked outcrops was obtained by means of a level, the datum-line adopted being either the nearest bench-mark, or the intersection of a neighbouring contour-line with some well-marked topographical feature.

iv. Literature.

The literature dealing specifically with the Hadleigh Road Area is almost negligible, as previous to the excavations of 1900, the railway cutting adjacent to the Hadleigh Road Area had been overgrown for many years, and apparently there had been no excavations since the railway line was originally constructed.

W. Whitaker referred to the cutting in the Survey Memoir (1) as follows:—"but little was to be seen of what must once have been a fine section." He, however, saw evidence of disturbance in the beds. The late F. W. Harmer also noted the cutting which, however, judging from a small section recorded by him, must have been in much the same condition as when seen by the officers of the Geological Survey.

The Ipswich district was visited by the Geologists' Association in 1907 and 1911 (2), and a few of the sections incorporated in the subsequent reports, but without detailed description. In a still more recent paper Professor P. G. H. Boswell (3) refers to the disturbed sections in their general relationship to the wider questions of the evolution of the Gipping Valley. A small party of geologists visited the district on the occasion of the Centenary of the Geological Society in 1907, a list of the members of the party being included in the Centenary Volume (4).

The section exposed at the Claydon Chalk Pit was figured and described by W. Whitaker in the Survey Memoir, but all the other sections have been excavated since the conclusion of the Geological Survey of the district (5).

Within recent years the prominence given to the study of the archæology of the district by the work of Mr. J. Reid Moir and the formation of the Prehistoric Society of East Anglia has led to a considerable literature on the flints found in various deposits in the district. The bearing of this work on the present investigation is confined to the pits of Messrs. A. Bolton & Co., and will be dealt with when these sections are described.

II. Geology of the Gipping Valley.

(a) Normal succession of the Beds.

The beds which crop out in the immediate neighbourhood are shown in the following table:—

6. Recent	..	Alluvium.
5. Valley Drift	..	{ Loam or brickearth.
(Post Glacial)	..	{ *Gravel and sand.
4. Glacial Drift	..	{ *Kimmeridgic boulder clay.
		{ *Brown bedded boulder clay.
3. Pliocene	..	{ *Gravel and sand.
		{ *Red Crag with coprolites at base.
		{ London Clay with cement-stone
		{ underlain by
		{ Pebble Beds—Oldhaven or Base-
		{ ment bed.
2. Eocene	..	{ Reading Beds, composed of fine
(Lower London		{ sands and plastic clays.
(Tertiaries)		{ Thanet Beds with green-coated
		{ flints at the base.
1. Cretaceous	..	{ Upper Chalk with flints. (Zones
		{ of <i>Belemnitella mucronata</i> and
		{ <i>Actinocamax quadratus</i>).

(b) General Outcrop of the formations.

The Gipping Valley is of pre-glacial age (3). For the purposes of this paper it is only necessary to consider the solid geology of a small portion of the valley between Ipswich and the village of Bramford, three miles to the north-west. Geologically this area forms part of the margin of the London Basin, (6) as there is a general thinning out of the Lower London Tertiaries to the north-west, the most northerly mappable outcrops of these deposits, as well as the most complete exposures, occurring in the neighbourhood of Bramford (12). The restriction of the outcrops of these formations to so limited an area is of great value when dealing with the source of origin and amount of

* Beds represented in the disturbed deposits of the Hadleigh Road Area.

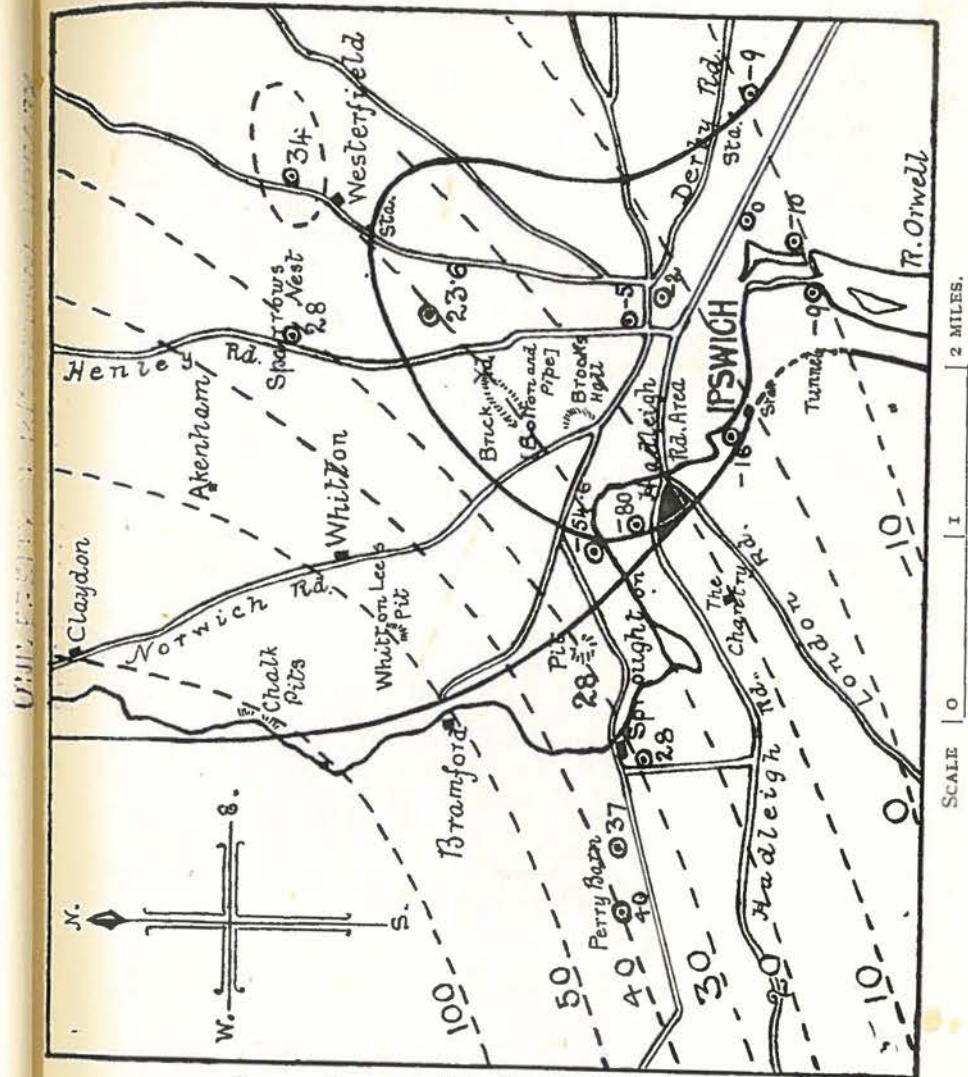


Fig. 15.—MAP OF PART OF THE GIPPING VALLEY, IPSWICH.

Stratum-contours of the upper surface of the chalk.

Wells ○ Heights in feet.

The gradient of the upper surface of the chalk is approximately 18 feet to a mile in this area.

The abnormal level of the chalk-surface at Ipswich is due to the presence of a deep glacial channel, which follows the general direction of the R. Gipping.

movement of the disturbed beds in the Hadleigh Road Area derived from these outcrops.

In the Bramford sections the outcrop of the chalk reaches the 100-foot contour, but its surface gradually dips to the south-east, so that in Ipswich, it sinks below O.D. (fig. 15). There is a corresponding change of level as well as variation in thickness of the Lower London Tertiaries in the intervening area. As a result of this general dip, outcrops of portions of these deposits occur at low levels bordering the terrace-gravels near the village of Sproughton (Thanet Beds over chalk) and the Hadleigh Road Area (Reading Sands), whilst in Ipswich the outcrop of the Reading Sands approaches the level of the River Orwell. It follows, therefore, that the floor of the pre-glacial valley between the Hadleigh Road Area and Bramford was composed of chalk, and the sides of the valley of Reading Sands (with Thanet Beds) overlain by London Clay, which again was capped by remnants of the Pliocene (Red Crag).

(1) Right Bank of the River Gipping.

The Pliocene outcrop on the right bank of the River Gipping is impersistent and can only be partially mapped on the one-inch scale. Towards Sproughton it is represented by ferruginous sands, but the evidence of recent well-borings proved the presence of shelly Red Crag beneath the plateau adjacent to the Hadleigh Road Area. The base of the Crag cuts across the beds of the London Clay. The junction between the London Clay and Reading Sands, however, is almost entirely obscured, the line of outcrop of the lower level of the London Clay adopted by the Officers of the Geological Survey near the disturbed area being admittedly open to correction (1" Geological Map, sheet 48 N.W.).

(2) Left Bank of the River Gipping.

Exposures on this side of the river are confined to a few brickyards, for the outcrops are largely obscured by drift. A few well-sections, however, give valuable information. Exposures showing the junction between the London Clay and Reading Sands are to be seen in the brickyards of Messrs. Bolton & Co., Ipswich, and at Whitton-Leys, but the exposure described in the Survey Memoir in the Brookshall Pit is now obscure.

(c) Brief lithological descriptions of the beds.

From the point of view of glacial disturbances the geological deposits of the district may collectively be divided into two lithological series—arenaceous and argillaceous, a division which is of equal importance when the individual formations are considered in detail. As the juxtaposition of these two

types forms a plane or surface peculiarly adapted for glacial disturbance it is necessary to emphasise the following points of structure:—

- (1) The different lithological composition of the upper part of the lower beds and the lower part of the upper beds of each of the local formations in contact.
- (2) The presence of intercalated bands of harder material in the individual deposits, such as cement-stone in the London Clay, and ferruginous bands in the Crag.

Based on this simple classification the lithology of the formations is briefly tabulated below:—

VI. Pliocene—Red Crag.	<ol style="list-style-type: none"> 3. Decalcified ferruginous red sands and gravels with bands of ironstone. 2. Comminuted shelly red sands with bands of ironstone, decalcified in places. 1. Coprolite bands embedded in shelly sands.
V. London Clay.	<p>Sandy and clayey loam. Both the lower and upper portions may be somewhat arenaceous.</p> <p>Hard bands of cement-stone at various horizons, selenite crystals, and pyritised plant remains.</p>
IV. Oldhaven Beds.	<p>Numerous rounded black flint pebbles embedded in fine sand.</p> <p>Broken shells in places.</p>
III. Reading Beds.	<p>Sharp white or mottled sand of fine grade with lenticles of plastic clay chiefly in the upper part, glauconitic or green towards the base.</p> <ol style="list-style-type: none"> 3. Reddish clayey greensand. 2. Green glauconitic clays or sandy loam. 1. Conglomerate of green-coated flints embedded in stiff clay forming the "Bull-Head Bed."
II. Thanet Beds.	<p>Chalk with flints.</p> <p>(Not exposed in the vicinity of Hadleigh Road.)</p>
I. Cretaceous.	<p>Chalk with flints.</p> <p>(Not exposed in the vicinity of Hadleigh Road.)</p>

(d) General levels of the Outcrops.

(1) The Chalk.

The gradient of the chalk surface is approximately 1/300 or about 18 feet to a mile, the stratum-contours having a general N.E.-S.W. trend. It will be seen from the map that

the approximate level of the chalk beneath the disturbed deposits of the Hadleigh Road Area is 10 feet above O.D. (fig. 15.)

Adjoining this area the surface of the chalk rapidly sinks to 80 feet below O.D. indicating the presence of a deep glacial channel (3). The extension of this channel across the valley was proved from the evidence of a well at Boss Hall, about half a mile to the north-east, where the level of the chalk is 54.5 feet below O.D. (fig. 15).

(2) London Clay and Pliocene.

Western side of Valley.

The junction between the London Clay and Pliocene in the immediate neighbourhood of the Hadleigh Road Area on the western side of the valley is approximately 90 feet above O.D. From the average thickness of the various deposits, the line of junction between the London Clay and Reading Sands is here estimated at a little below the 50-ft. contour. It is most unfortunate that records of the deep artesian well sunk many years ago in the neighbouring Chantry Estate have been lost, and there are no reliable particulars of a later well sunk on the same estate. A considerable number of shallow wells, averaging 30-40 feet in depth have been sunk in this area within recent years, but few reliable records are available.

Eastern side of the Valley.

On the eastern side of the Gipping Valley the exact level of the base of the London Clay (or doubtful Oldhaven Beds) is as follows:—

- | | | |
|--------------------------------|----|--------------------|
| (1) Messrs. Bolton & Co.'s Pit | .. | 63 feet above O.D. |
| (2) Westerfield Brewery Well | .. | 64 " " " |
| (3) Henley Road Well | .. | 61 feet O.D. |
| (4) Brookshall Pit | .. | 56 + " approx. |
| (5) Whitton Leys Brickyard | .. | 83 " " |

On this side of the valley the various outcrops are largely obscured by drift, and there has been considerable glacial disturbance of the upper part of the London Clay and later deposits.

(3) Reading Sands and Thanet Beds.

In the Hadleigh Road sewer section, what appears to be the base of the Reading Sands and top of the Thanet Beds occurs at 16 feet above O.D. This section is described later (Part II, p. 183). In some well-sections these two formations are classed together, but in the limited area of the Gipping Valley here considered, the level of the base of the Reading Sands may be taken as approximately 6 feet above the chalk (levels indicated in fig. 15).

e. Level O.D. of geological formations between Ipswich and Bramford.

	FORMATION.	LEFT BANK OF R. GIPPING.	FEET LEVEL O.D.	RIGHT BANK OF R. GIPPING.	FEET LEVEL O.D.
1.	Top of Chalk = base of Thanet Beds	Claydon Pit Bramford Pits Sproughton Pit Henley Road Well	100 + 100 app. 28 23' 6"	Sproughton Well (Cobbold's allotments)	37
2.	Top of Thanet = base of Reading Beds	Bramford Pits Henley Road Well	107 30	Hadleigh Road Area	16 app.
3.	Top of Reading Beds = Oldhaven Beds = base of London Clay	Bramford Pits Whitton Leys Pit Bolton & Co.'s Pit Brookshall Pit Henley Well	125 83 63 56 + 61	Grindle Farm Sproughton district Ipswich Tunnel	50 app. 30
4.	Top of London Clay = base of Crag			Area between Sproughton and Ipswich	85 app.

(f) Thicknesses of the various geological formations.

Particulars of the thicknesses of the several geological formations in the immediate neighbourhood are indicated in the table. It will be noticed that the full thickness of the London Clay is seldom shown. The thickness of this formation is best indicated on the map of the isopachytes of this formation constructed from data obtained from a much wider area. This map indicates the average thickness of the London Clay in the neighbourhood of the Hadleigh Road Area as between 30 to 40 feet (6).

The approximate thicknesses of the geological formations adjacent to the Hadleigh Road Area are therefore as follows:

- | | | | |
|-------------------|----|----|-------------|
| (1) Thanet Beds | .. | .. | 6 feet. |
| (2) Reading Sands | .. | .. | 30 feet. |
| (3) London Clay | .. | .. | 30-40 feet. |
| (4) Red Crag | .. | .. | Variable. |

(g) Levels of the geological outcrops near to the Hadleigh Road Area.

From the various sources of evidence already indicated, the upper levels of the various geological outcrops adjacent to the Hadleigh Road Area are approximately as follows:

- | | | | |
|-------------------------|----|----|-------------------|
| (5) Base of Pliocene | .. | .. | 85 ft. above O.D. |
| (4) Top of London Clay | .. | .. | 75-85 ft. O.D. |
| (3) Top of Reading Beds | .. | .. | 45 ft. O.D. |
| (2) Top of Thanet Beds | .. | .. | 16 ft. O.D. |
| (1) Top of Chalk | .. | .. | 10 ft. O.D. |

III. Detailed Description of sections in the disturbed areas.

I. THE PIT OF MASON'S PORTLAND CEMENT CO., CLAYDON.

This pit, which was opened about the year 1907, is situated half-a-mile south-west of Claydon railway station, and about 4 miles north-west of Ipswich. The site of the pit is a little north of the outcrop of the Lower London Tertiaries, the geological formations in the immediate district consisting of chalk and drift deposits. Four preliminary borings proved that the average depth to the chalk in the district surrounding the pit was 50 feet. The site of the pit was chosen with great care, one half being entirely in chalk, the other in stiff boulder clay, each deposit having now being worked to a depth of about 50 feet.

Particulars of the four borings are as follows:

No. 1 BORE. JUNE 3rd, 1912.

Depth	4' 0"	Sand	4' 0"	
"	8' 6"	Boulder clay	4' 6"	
"	15' 6"	Loamy gravel	7' 0"	
"	30' 0"	Clay	14' 6"	composed of—
		Black clay and sandstones	.. ..	1' 0"
		Pure clay	.. ..	2' 6"
		Very chalky clay	.. ..	6"
		Marly gravel	.. ..	9"
		Marly clay	.. ..	9"
		Marly gravel	.. ..	9"
		Chalky clay mixed with sand	.. ..	8' 3"
				Total .. 14' 6"

"	31' 6"	Sand	1' 6"
"	55' 6"	Clay	24' 0"
"	56' 0"	Sand	6"
"	58' 0"	Chalky clay	2' 0"

No. 2 BORE.

Sand, gravel	.. ..	6' 9"
Blue clay	.. ..	33' 6"
Brown clay	.. ..	2' 3"
Flints	.. ..	9"
Chalk	.. ..	To Chalk 43' 3"

No. 3 BORE.

Gravel and sand	.. ..	4' 6"
Brown clay	.. ..	4' 0"
Blue clay	.. ..	33' 9"
Brown clay	.. ..	2' 3"

Chalky sand	.. ..	2' 0"
Flints	.. ..	1' 0"
In Chalk	.. ..	3' 0" To Chalk 47' 6"

No. 4 BORE.

Top soil, brown clay	.. ..	7' 0"
Blue clay	.. ..	37' 9"
Brown clay	.. ..	11' 6"
Flints	.. ..	6"
Chalk	.. ..	To Chalk 56' 9"

No. 1 Bore shows the variable nature of the beds above the chalk, in contrast to the other three, where boulder clay is the chief constituent of the drift deposits.

From the point of view of glacial disturbances the pit is of interest as it showed a clearly defined line of junction between disturbed chalk on the south side, and stiff boulder clay on the north, a lenticle of sand being pinched in between the two in the lower part of the excavations. The characteristics of these three deposits are as follows:

a. The Chalk.

The chalk belongs to the zone of *Actinocamax quadratus*; a specimen of *A. granulatus* was obtained in 1915, but fossils are rather scarce; flints also are not very numerous. The chief interest of the chalk lies in a brecciated and disturbed zone which extends from the line of junction between the chalk and clay and gradually rises to the upper part of the chalk-pit to the south. On the eastern side of the pit this brecciated zone had a maximum thickness of about 30 feet, but on the opposite or western side the disturbed chalk was confined to the immediate junction with the clay and the top 10 feet.

Unlike the sections in the Royston Chalk, there was only a partial development of anticlinal structure, (9) and the brecciated zone did not present features of an unusual character. On the other hand the chief centre of interest lay where the chalk was in juxtaposition with the clay. The line of junction between the two took the form of a sigmoid curve, the contact face of the chalk being very smooth and polished. The form of this curve and the relationship of the beds is shown in the sections (figs. 16 and 17).

In 1915, Dr. J. W. Evans, F.R.S., drew my attention to the thrust-planes associated with this face of chalk. Subsequent detailed study showed that the sigmoid curve was due to the superposition of numerous lenticles of chalk associated with thrust-planes inclined at various angles, stained with limonite and uncontaminated with boulder clay (fig. 16). As the sigmoid curve is of general occurrence in disturbed glacial

deposits, it may be regarded as a definite structural unit in glacial tectonics, being composite in structure and, when complete, forming a major glide plane for the movement of later material (10). With the completion of this curve the chalk became a minor "horst" against which further material was moulded, the subsequent structure of which varied according to the lithology of the beds involved. The sections in Bolton's Brickyard, to be described later, show that the same curve is also developed in London Clay when this is subjected to glacial disturbances. The arrangement of the thrust-planes in Mason's Pit is shown in the section (fig. 16).

b. The Sand.

The lenticle of sand caught in at the sigmoid curve between the chalk and boulder-clay is of interest both from its position, and also from its lithological characteristics.

The sand showed signs of compression, the bedding being wavy and contorted (fig. 17). It thinned out both east and west, the maximum thickness being 15 feet, and the length of the lenticle from north to south about 30 feet. In one part it rested on a polished surface of chalk. Above, it thinned out in the form of the apex of a triangle. On the western side of the cutting, wisps of sand occurred at the junction of the clay and chalk. In places, the roof of the chalk above the sand showed signs of solution, whilst the relationship between the boulder clay and sand clearly demonstrated the squeezing action to which the sand had been subjected (figs. 16 and 17).

Lithologically, the sands are also of much interest. They contain much chalky material in the form of chalk-gravel, and layers of chalk pebbles about the size of peas, associated with bedded chalk rubble. The mineral composition of this sand has been described by Professor P. G. H. Boswell (7), and also in a letter to the author in 1915. His main conclusions are as follows:

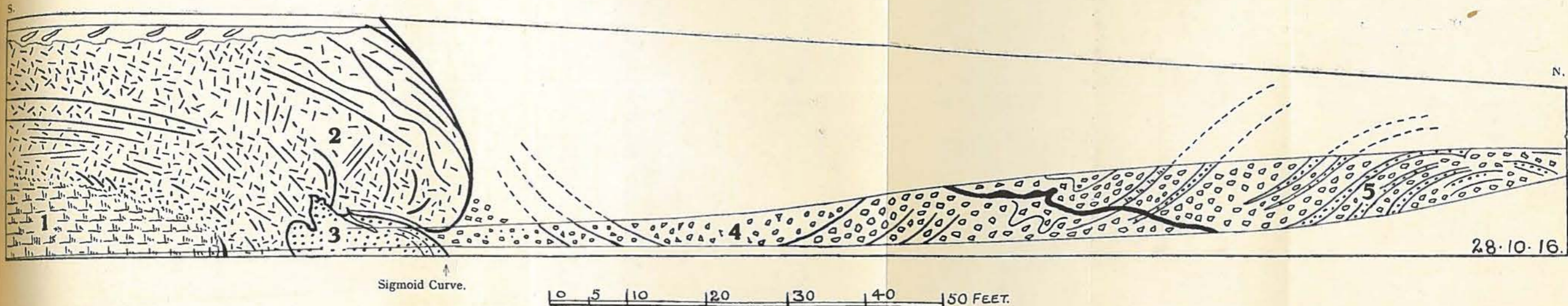
- a. There is an unusual amount of glauconite, pointing to the incorporation of material derived from the Thanet sands, that is, from the north or north-west and beyond the present outcrop of this formation.
- b. The most important and extraordinary point is the wonderful rounding of the quartz and felspar of diameter from 0.5 to 2 mm.
- c. It was suggested that the rounding of the grains was possibly due to gyrotory water currents in a subglacial channel. In this case the rounding is as perfect as that of desert sands rounded by wind action.

The pinching out of the sands clearly demonstrates that the action of a subglacial stream took place prior to the deposition of the boulder clay. The sand in its present position



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SCALE.

FIG. 16.—MASON'S CHALK PIT, CLAYDON, 1915-16.

5. Light-coloured chaly Boulder Clay with sandy intercalations forming a small anticline. Upper portion of Boulder Clay removed.
4. Very dark Kimmeridgian Boulder Clay. Near the chalk face the clay contains few pebbles, but elsewhere is very chaly.
3. Glacial sands occupying a hollow in the brecciated chalk. The sands are much compressed below, but thin out laterally. Solution of the chalk was shown in places. The dark band between 4 and 5 separates two types of boulder clay and consists of pebbles.
2. Brecciated chalk associated with thrust planes, which generally increase in dip and ultimately coalesce in the "sigmoid-curve."
1. Chalk *in situ*.

[NOTE.—The drawing of the southern part of this section had been reversed in order to show the relationship of the structure as a whole.]



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is a " remnant " of what appears to have been a much more extensive deposit.

c. The Boulder Clay.

The boulder clay consists of the stiff Kimmeridgic boulder clay full of Jurassic boulders similar to the widespread deposits which occur over a considerable area. The clay, however, contains irregular patches of chalky gravel, and towards the base is different in character, being bedded and intercalated with thin strips of sand and gravel. This lower deposit is of special interest as it showed a small anticlinal structure (fig. 16).

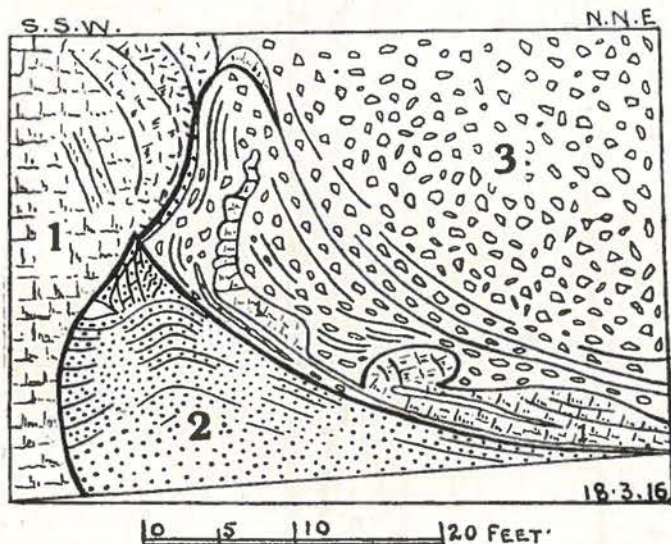


FIG. 17.—WESTERN SIDE OF MASON'S CHALK PIT, CLAYDON, 1916.
Junction between Chalk and Drift Deposits.

3. Kimmeridgic Boulder Clay, with incorporated chalk near the base.
2. Glacial sand, containing chalk grains, occupying a hollow in the face of the chalk, which showed signs of solution in places. The sand was much disturbed.
1. Chalk, brecciated above, compact below. The chalk below (2) was smooth and rounded.

Adjacent to the sigmoid curve the boulder clay contained a broken and inclined lenticle of chalk, which, from its position clearly proved that the movement of the boulder clay at this point has been almost vertical in the upper part, whilst below, as the clay rested on a smooth inclined plane formed by the surface of the disturbed sands, the movement proceeded at a gradually increasing angle. Hence the line of junction of the chalk and sand formed a glide plane for the passage of the boulder clay (fig. 17).

ANALYSIS OF THE STRUCTURE.

Taking the base of the sigmoid curve and reviewing the evidence as to the direction of movement indicated by the run of the thrust-planes in the chalk, and the position of the chalk mass included in the boulder clay, it is clear that the angles of the various directions of movement have varied from a low angle of say 30 degrees (indicated by the basal layers of brecciated chalk), to a vertical position in the case of the boulder clay adjoining the sigmoid curve. This almost vertical rise of the boulder clay is analogous to the movement in ice. Mr. G. W. Lamplugh, on seeing the section, drew my attention to his paper on Spitsbergen Glaciers, where he has described a similar phenomenon observed by him in the Von Post Glacier where englacial material is carried up at a high angle and outcrops on the surface of the glacier (11).

Another point of some significance is the small anticline in the boulder clay. The cause of this structure can only be attributed to the effects of accumulated pressure caused by the obstruction to movement at the sigmoid curve.

II. LARGE CHALK PIT AT CLAYDON (2, Plate V, fig. 7, 1907).

This interesting section has been known to geologists for many years, and was described by the late W. Whitaker in the *Survey Memoir* on Stowmarket, a portion only of the section being figured (5). In the years 1906-7 I cleared all the lower part of the section, which consisted of disturbed deposits resting on the top of the chalk. This section was ultimately drawn to a scale of 20 feet to an inch and completed in January, 1907. It was only by constructing a platform along the top of the chalk and carefully picking out the beds that the details were traced.

A second section showing further details in the southern-part of the pit was completed in December, 1915, after which date the pit was unfortunately abandoned. The disturbed deposits in this pit are much more varied than those of Mason's Pit, the platform of movement in this case being a horizontal deposit of Thanet Beds resting on chalk. Disturbances of the chalk were confined to a slight "bending over" of the upper part, in one place down to 20 feet, but a large boulder of chalk, 42 feet long, rested on the lower "bull-head conglomerate" of the Thanet beds (fig. 18).

The sections, 1907, 1915.

The disturbed beds consist of Thanet Clays, ferruginous sands (? decalcified Crag), and drift deposits (sands, gravel, boulder clay).

These beds are arranged as shown in the sections. In this case the surface of the Thanet Beds has become a horizontal!

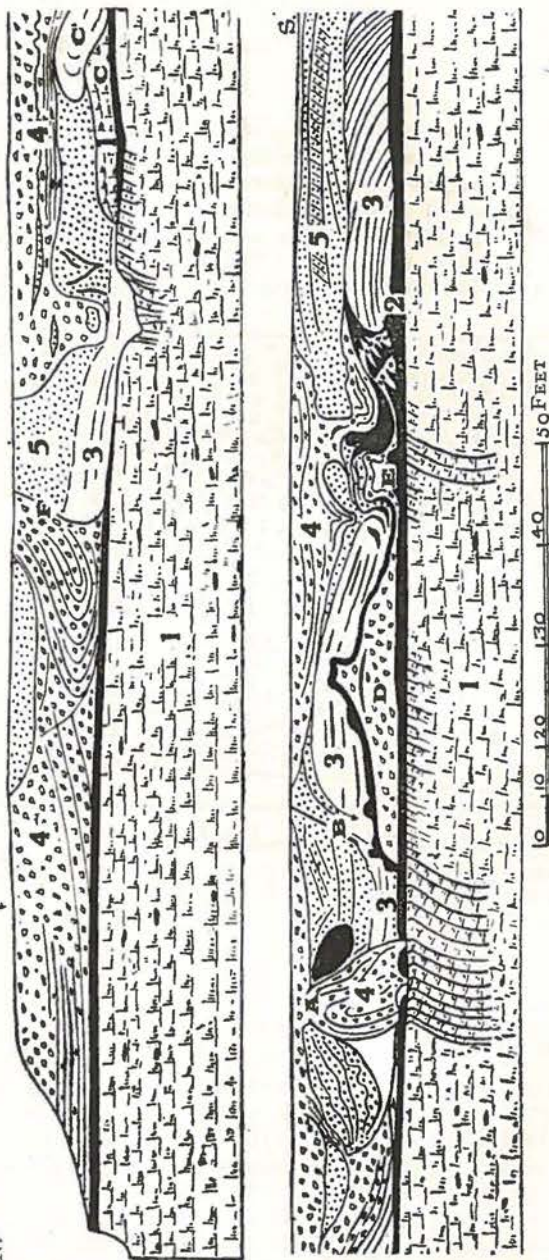


FIG. 18.—SECTION OF THE TOP OF CLAYDON CHALK PIT, 1915.

5. Glacial sands and gravels.
4. Buff boulder clay, bedded and contorted in places. A = Strike section of remains of overfold. D = Wedge of boulder clay. F = Sigmoid curve.
3. Ferruginous and decalcified Red Crag, with coprolites at the base in places.
2. Thanet Beds, much of which occupies an anomalous position. The bed immediately resting on the chalk consists of green-coloured flints forming the "Bull-Head Bed," and is *in situ*.
1. Chalk *in situ* but disturbed in places. Transported boulder of chalk at C.

glide-plane for the passage of transported material. In describing the structure we are limited in this case by the fact that the beds are only viewed in two dimensions.

Certain conclusions, however, may be drawn as to the order of events leading to the production of the present structure. These are as follows:

- a. The upper few feet of plastic Thanet Clay has been planed off, leaving the hard basal conglomerate as the main platform over which material has been transported.
- b. The chalk boulder (fig. 18, C) was displaced and transported to its present position before the deposition of the later material which overlies it (C¹). The upper surface of this boulder C has a *roche-moutonnée* outline.
- c. Sand, gravel and ferruginous sands (? Crag) were moulded over and against the chalk boulder (C¹).
- d. Boulder clay of a sandy, bedded nature passed over the surface of the deposits C¹, moved downwards and over the horizontal Thanet Beds, and a portion of this boulder clay was then deposited as a wedge-shaped mass, D, having a *roche-moutonnée* outline in the southern part of the section. The interesting contortions associated with the sharp edge of the boulder clay wedge are shown in the 1915 section (fig. 18). This section clearly shows the effects of horizontal movement and friction along a surface of plastic clays, leading to cessation of movement of the wedge of boulder clay.
- e. Incorporated with the boulder clay were the following beds:
 3. Sand and gravel.
 2. Ferruginous sands.
 1. Thanet Clays.

Obstruction to movement caused by the wedge-shaped mass of boulder clay D, led to the moulding of Thanet Clays on its upper surface, and the formation of a small sigmoid curve on its "exposed" side; against this curve (B) the hard ferruginous sandstone A-B was wedged, leading to the production of the small overfold A, in the boulder clay. Further evidence of compression and obstruction to movement are shown by the curves in the boulder clay towards the north of the section (F), where a larger sigmoid curve was developed. In the later section in 1915 (fig. 18), the position of the smaller sigmoid curve (B) is occupied by a well-developed thrust-plane, whilst the sandstone A-B is wedged in as a compressed mass. The inversion of the Thanet Beds is the most striking feature of this section.

III. THE BRICKYARD OF MESSRS. A. BOLTON & CO., IPSWICH.

This brickyard is situated about a mile north of Christchurch Park, Ipswich, and has been opened since the conclusion of the Geological Survey of the district.

The geological structure of the pit is quite simple. The basal formation consists of Reading Sands overlain by shelly pebbly beds of ? Oldhaven age, which again are overlain by the basal beds of the London Clay. Prior to the year 1907 there was no evidence of disturbance in the pit, a good face of London Clay being capped by sand and gravel. As the face of the clay was worked back in the direction of the adjoining railway line the pit gradually took the form of two basin-shaped hollows filled with sand, with an intervening mass of London Clay. The hollows were waterlogged, but the water was gradually drained off into ponds in the pit. The rapidly increasing depth of the sand in the two hollows proved that the slope of the London Clay beneath was fairly steep. As the two "basins" became more clearly defined, all the upper part of the London Clay showed an anomalous structure, the lowermost 12 feet, however, being normal. Hence the disturbances, as pointed out to me by W. Whitaker, were superficial, whatever the cause, and not connected with earth-movements. Moreover, they were local.

Widespread interest in this pit was aroused by the discovery of the chipped flints in the lower deposits of the "basins," alleged by Mr. J. Reid Moir to be of human workmanship, and the lower ferruginous sands where the flints occurred, were claimed to be basal Crag deposits from their contents. The question, therefore, as to whether these deposits were *in situ* or displaced became of general interest and of some importance, and led many geologists and archæologists of repute to visit the locality.

The description of the deposits thus falls under two well-defined headings: (1) the London Clay, and (2) the material occupying the two basins. My investigations have taken the form of recording the structure shown in all new excavations by means of sections usually drawn to a scale of 10 or 20 feet to the inch. The investigation of the contents of the basal deposits of the two basins has been conducted by Mr. J. Reid Moir, and these researches, although primarily from an archæological standpoint, have led to the accumulation of some useful geological data.

The lithology of the deposits also falls into two well-marked divisions, A. London Clay; B. Sand filling the two basins.

a. The London Clay. (2, 1911, Plate VII.)

Lithology.

The London Clay in this pit may be divided into the following classes:—

Sigmoid Curve.

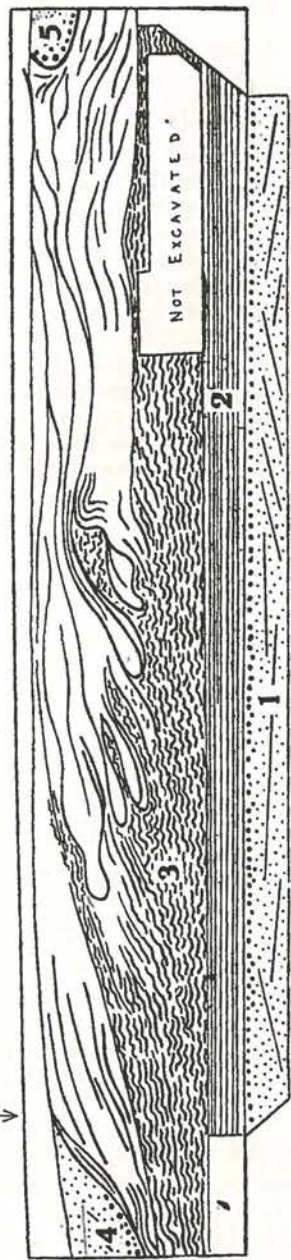


FIG. 19.—SECTION OF THE NORTH SIDE OF THE BRICKYARD OF A. BOLTON & Co., LTD.
About a mile north of Christchurch Park, Ipswich, 1915.

5. Glacial sand and gravel with basal bed of the Red Crag below, forming the "Eastern Basin."
4. Sand and gravel with basal bed of the Red Crag forming the "Western Basin."
3. Puckered London Clay showing strain-slip cleavage, passing upwards into transported lenticular masses of London Clay associated with curved thrust planes. "Sigmoid Curve" developed between 3 and 4.
2. Undisturbed basal bed of the London Clay, immediately underlain by pebbly gravel, fossiliferous in places, which represents the Oldhaven Beds.
1. Cross-bedded Reading Sands.

(1) The lower sand. (Basal bed of the Red Crag).

The lower ferruginous sand is only a few feet in thickness, and is associated with flints which occur in small hollows in the clay beneath.

Mr. Moir's general conclusions on this deposit are as follows:—

- (a) The detritus bed is similar in composition to the basal bed of the Crag seen elsewhere in its normal position in undisturbed sections.
- b. The bed in the two "channels" contains practically no extraneous material, not found in the basal bed elsewhere; hence there has been no redeposition of the material.

The detritus bed has been subjected to movement, as this bed follows for some distance the abrupt upward slope of the London Clay on either side of the hollows, which is an abnormal arrangement. Moreover, it rests on contorted London Clay (2), 1911.

Mr. J. Reid Moir's evidence has convinced me that the lower deposit in the two basins represents the base of the Crag, but in an abnormal position. In its relationship to the London Clay the sections also suggest that this bed, and the clay immediately below it, *have been moved together as one lenticle or mass*. With this view Mr. Moir is in agreement.

(2) Sand in the "channel" (basins). (2, 1911, Pl. VII.)

The sand in the lower "channel" was analysed by Dr. H. F. Harwood and was found to contain 96.20 per cent. of SiO_2 . The upper part contains lenticles of gravel and a little loam; below it becomes much stained with iron oxide. There is no doubt the sand is water-sorted and deposited. On the other hand, portions of the sand in the upper "channel" are associated with thrust-planes and a wedge of London Clay; moreover, they show a peculiar type of bedding (fig. 20).

Description of the Sections.

The first scale section of the northern part of Bolton's pit was completed in July, 1910, and published in 1911 (2). The section shows a horizontal surface of undisturbed London Clay overlain by disturbed London Clay forming a central mound, flanked on the east and west sides by the two "channels" (basins) containing the sand. This section clearly demonstrates that the basal beds in the two "channels" are in an abnormal position.

Between the years 1910 and 1915 considerable developments in the pit occurred and an extremely fine section, exposed in the latter year, showed to great advantage the tectonic structure. Portions of this section are illustrated in figs. 19 & 20. The lower or western "channel" had become wide in 1915; the puckered London Clay overlying the undisturbed clay is thin below the

western "channel," but becomes banked up in the central part of the pit; this clay is riddled with thrust-planes, and is characterised by strain-slip cleavage. Overlying, and arising from this mound, other lenticles of London Clay are arranged along gracefully curving thrust-planes, which again dip below the base of the eastern "channel," where this zone becomes thinner.

The easterly face of each channel shows the sigmoid curve (figs. 19 and 20) and the run of the thrust-planes clearly indicates that this curve is of composite structure due to the superposition of thrust-planes resting at various angles of

Sigmoid Curve.

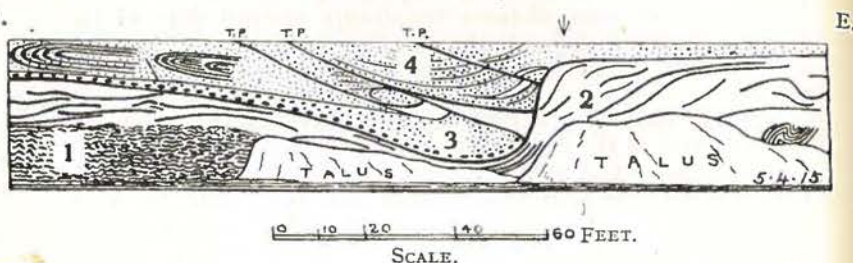


FIG. 20.—BRICKYARD OF A. BOLTON & CO., IPSWICH, 1915.

"Eastern Basin" showing "Sigmoid Curve" in London Clay, and "Thrust-Planes" in the sand.

4. Glacial sands and gravels containing wedges of displaced London Clay, intersected by thrust-planes (T.P.).
3. Ferruginous sandstone with flints at the base. Represents basal bed of the Red Crag.
2. Disturbed London Clay associated with thrust-planes, the face adjacent to beds 3 and 4 forming a "sigmoid-curve" This bed passes below to 1.
1. London Clay, much puckered and showing strain-slip cleavage. In places it contains more sandy portions of London Clay, which are unpuckered.

inclination, a feature already demonstrated in the chalk-face of Mason's Pit (figs. 16 and 17).

The order of events would appear to be as follows, beginning from below upwards, number 5, being the last event, and the conclusion of the structure.

5. The infilling of the basins by thrusting in the eastern basin and by water-action in the western.
4. The stranding of the "detritus" bed.
3. The formation of two sigmoid curves.
2. The passage of lenticles of London Clay over the lower puckered beds.

- i. The rucking of a horizontal surface of London Clay and the construction of a central mound of intensely squeezed clay.

With reference to the larger or western basin, the banking of London Clay beneath and against the western end has led to the formation of a curve and what appears to be an attempt at a fold. This basin is a parallel case to the mass A-B of Claydon Chalk pit, but shown more clearly in (2), 1907, Plate V, fig. 7. Pressure due to the buttressing of the lower beds at the sigmoid curve has led to compression in both cases.

General points on the structure.

The evidence serves to show that, in its structure, the central puckered mass of London Clay was of roche-moutonnée form, with thrust-planes on the western or exposed side. This form is entirely composed of, and built up from, material transported and stranded by glacial action. The plastering of material by thrust on the one side and by movement under lessened pressure on the other, has gradually moulded this form, ultimately producing sigmoid curves, which have acted as the exposed sides of minor horsts. Hard sandy material in its subsequent passage made an abortive attempt to ascend these faces of sigmoid form.

The wedge of London Clay in the eastern basin (fig. 20) shows that transportation of lenticles of London Clay also occurred. This point will be emphasised when dealing with the next pit.

More recent excavations show that the disturbances extend at the extreme westerly corner of the brickyard, down to the underlying Reading Sands, proving that the complete thickness of the London Clay had been exposed to ice-action. As the outcrop of undisturbed London Clay in Bolton's Pit is below the normal thickness as shown by the plotting of isopachytes, the range in lithology shown in the disturbed portions of the clay may well represent different zones originally occurring in the undisturbed outcrop in the immediate neighbourhood

IV. THE SAND PIT OF MESSRS. A. BOLTON & CO., LTD.

This pit adjoins the brickyard already described, but lies at a slightly higher level (above the 100-ft. contour) a little to the east; both pits are situated between the Henley and Norwich Roads. Adjacent to the pit is a group of houses known as the Prospect Cottages.

The sand and gravel have been worked for many years for building purposes. The earliest sections recorded by me were completed in January, 1904. They were seen in trenches and pits in the floor of the pit.

The sands and gravels were mapped by the Survey as glacial and were erroneously named by Wood and Harmer "Middle Glacial" deposits, a term not adopted by the Survey,

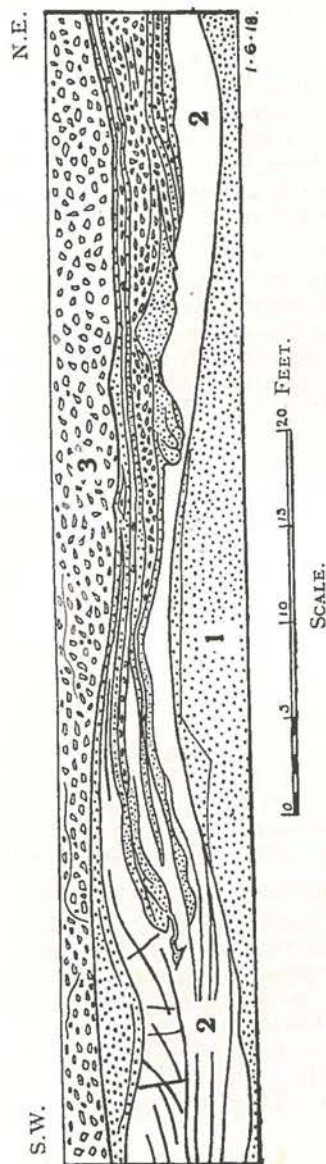


FIG. 21.—SAND-PIT OF A. BOLTON & CO., IPSWICH, 1918.

3. Boulder Clay;
 2. Transported loam derived from the London Clay, rotted cement-stone occasionally being found. The loam is associated with interbedded glacial sands and gravels and boulder clay. The lines in the loam represent thrust-planes or planes of movement, with occasional cross-fractures.
 1. Glacial sands and gravels forming a mound or dome, against and over which beds 2 and 3 have been deposited.

as being decidedly misleading. The trench sections of 1904 showed cross-bedded white sand overlain by other sands containing lenticles and fragments of loam, a fairly well-marked line of division occurring between the two. The petrology of the lower sands has not yet been worked out; at the present time there are no exposures, hence the possibility exists that they may represent an outcrop of the Upper Crag series. The lenticles of loam puzzled me for many years, but from their association with the sands above, which ultimately pass into undoubted glacial gravels, they may be classed as of glacial origin.

As the pit was further extended a considerable amount of gravel and sand overlain by boulder clay was excavated. This material is of glacial origin and has yielded the following derived fossils (8):

Purpura lapillus and rolled sharks' teeth (Crag), *Ostrea deltoides*, *Gryphaea dilatata* (Corallian-Kimmeridgian), *Otodus obliquus*, mineralised bones (? Cetacean and Proboscidean), and a specimen of lignite (? oak).

The list of derived fossils is typical of deposits of re-arranged glacial clays in this district. It will be noted that they are derived from both local and distant sources. Quartzite pebbles, which also occur, are probably from the Bunter pebble bed of the Eastern-Midland area.

Excavations in 1915 along the northern face of the pit were of special interest, on account of the appearance of a thin bed of what appeared to be London Clay, forming the base of the boulder clay and resting on an irregular surface of the gravel and sands.

This section was drawn to a scale of 10 ft. to the inch (fig. 21).

At the extreme south-western end of the section the clays occupy a small hollow in the gravel, and the lower clay occupies a persistent zone along the top of the gravel. The presence of rolled cement-stone in the lower clay suggested that it was London Clay. A specimen was submitted to Professor Boswell, who was satisfied that the brickearth was mineralogically uncontaminated.

The sections in the pit were recorded from 1915 onwards but the most instructive exposure occurred in the spring of 1918.

The section June 1st, 1918 (fig. 21), shows a rise of the lower sandy floor in the south-westerly part of the section, in the form of an arch or dome. Overlying this floor and flanking the slopes, the London Clay showed a remarkably interesting structure. The south-western side showed thrust-planes, whilst the north-eastern flank showed London Clay intercalated with sand and boulder clay, and displayed the phenomena of viscous-flow extremely well.

These sections link up the phenomena seen in the two pits, as due to one connected series of events, the structure seen in the sand pit being the latest stage of the glacial tectonics. The phenomena in the sand-pit show the gradual dying away of disturbance towards the more horizontal surface of the surrounding plateau. It also indicates a concentration of glacial drainage prior to the deposition of the boulder clay and transported lenticles of London Clay.

The thin strips of London Clay represent layers of englacial material, and are paralleled by similar material which occurs in the Hadleigh Road Area one mile on the other side of the valley, to be described later in Part II.

The publication of this work has been aided by a grant from the Publication Fund of the University of London, for which I express my best thanks.

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*PART 2.—THE STRUCTURE OF THE DISTURBED DEPOSITS OF THE HADLEIGH ROAD AREA, IPSWICH.

I. Introduction.

i. Location of Area.

The Hadleigh Road Area consists of a small, compact and well-defined triangular piece of ground in area about 10 acres, forming part of a low hill, west of the Handford Bridge, and about a mile north-west of Ipswich Station. It is bounded on the north-west by a railway cutting, between the London Road and Hadleigh Road overline bridges, these two roads meeting at the easterly corner of the area and forming the other two sides of the triangle (fig. 22).

ii. History of the excavations.

The study of the Hadleigh Road Area has now extended over a period of twenty-three years, during which time there have been extensive excavations by the railway authorities, and the Ipswich Borough Corporation (maps, figs. 22 and 23). During that period practically the whole of both sides of the railway embankments have been cut back for the purposes of widening the line and affording railway facilities for newly established engineering works. These excavations commenced in 1900 on the north-eastern side and extended for about half the length of the cutting from the London Road; in 1913 the remaining half was excavated to provide a line to the newly-established Diesel Engineering Works, the other half of this side of the embankment afterwards being "trimmed," thereby revealing the previous section of 1900, but showing further details. From the autumn of 1905 to 1909 a large number of the Ipswich "unemployed" were engaged at various intervals in excavating the hill from the Hadleigh Road to the railway cutting, reducing the hill to an inclined plane suitable for building sites. Again in 1911 nearly the whole of the south-western side of the railway embankment was excavated. The laying down of a sewer in 1913 along the Hadleigh Road to the Diesel Works exposed a long and continuous section of much value, the work occupying a period of nearly six months. In the same year a well was sunk for the Diesel Engineering Company (now Messrs. Vickers-Petters, Limited), 500 feet from the Hadleigh Road over-line bridge and adjoining the railway line, the position being marked by a water-tower. This well proved the presence of a deep glacial channel cut into the chalk. The Hadleigh Road Area remained a piece of waste ground for many years, but in 1917, sections seen in a series of trenches excavated for military

* Part III. of Thesis approved for the Degree of Doctor of Science in the University of London, 1926.

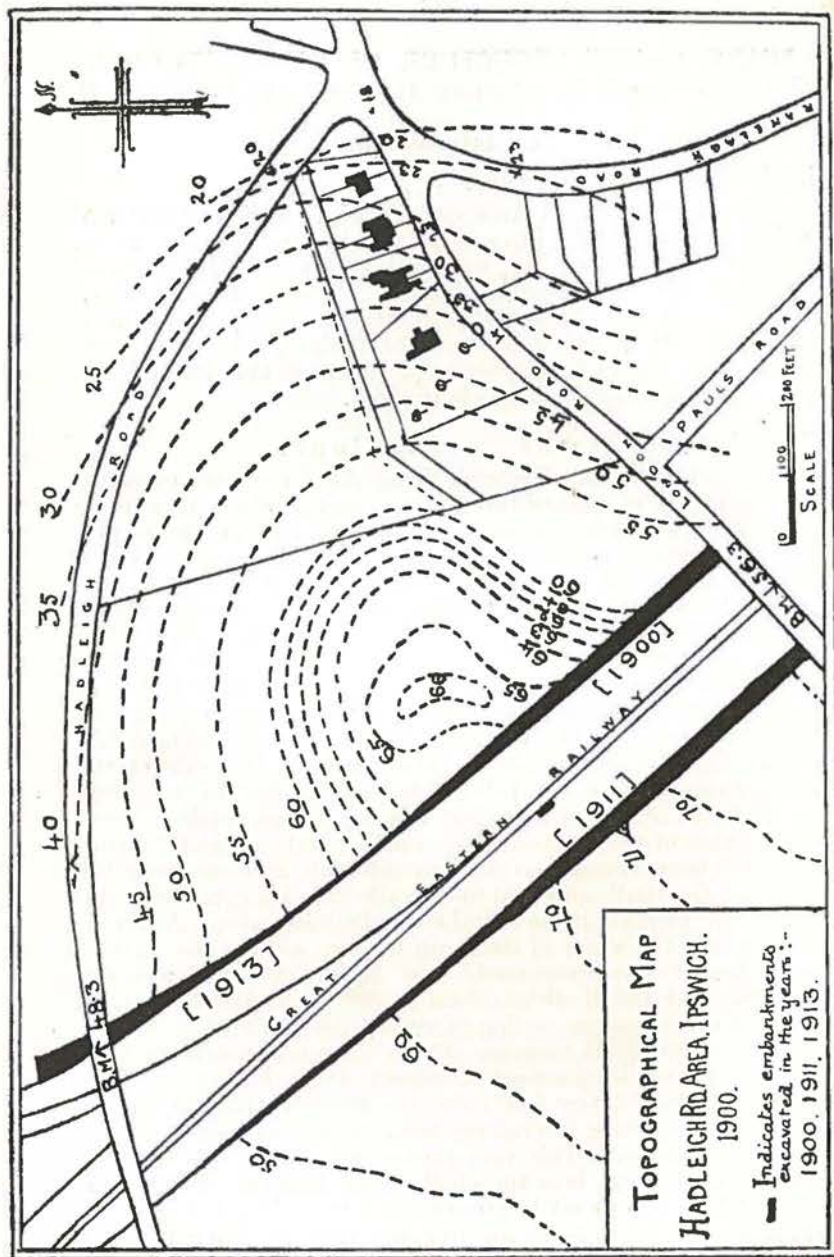


FIG. 22.—The map shows the outline of the hill before excavations were commenced, and is an excellent example of glacial topography.

purposes were carefully recorded; a geological map was also completed in the same year.

In 1919, after a period of ten years, the Ipswich Corporation commenced their long-deferred Housing Scheme. Various trenches were excavated, their positions were marked on a plan, and a small number of fresh sections were recorded. Between the years 1919-23 a further excavation of the small hill adjoining the London Road took place. It may be mentioned that extensive plans for the further cutting back of the north-eastern bank of the railway cutting, that is, along the site of the 1900 excavations, were prepared by the Great Eastern Railway Company, and sanctioned by Parliament in 1915, but owing to the European War these have unfortunately been indefinitely postponed. As there appears to be no immediate prospect of any further excavation, the time seems opportune for putting the observations on record.

A feature of some value in the numerous sections displayed from time to time, is the fact that the beds have been studied in three dimensions; from the serial sections and the geological map it is therefore possible to obtain a detailed knowledge of the tectonics of this limited area.

II. Detailed description of sections in the disturbed area.

I. THE SOUTH-WESTERN SIDE OF THE RAILWAY CUTTING, 1911 (plate 2, fig. 1).

This section is about a quarter of a mile long, and extends from near the Hadleigh Road overline bridge to the end of the cutting south-west of the London Road Bridge. The level of the rails is 33 feet above O.D. and the maximum height of the cutting 40 feet. Reading Sands crop out on the floor of the cutting and in the "cores" of the asymmetrical curves of London Clay on the sides of the cuttings. This section shows two separate masses of London Clay, the lentils of which are in places interbedded with boulder clay, each forming asymmetrical curves, the long sweeping curves of which are followed by short steeply-dipping curves, the latter showing good examples of tip-heap structure. Isolated lentils of Crag resting at various angles occur on each side of the curves. The central hollow between the two masses of London Clay is filled with indeterminate and mixed sands, derived from various sources, and containing a large isolated slab of London Clay. The line of section cuts diagonally across the strike of all the deposits. Boulder clay occurs in the two hollows adjoining the overline bridges at each end of the cutting. The section gives a clear example of over-rolling motion of the upper beds over the London Clay. The bedded strips of Crag, sand, and London Clay resting at fairly high angles adjacent to the

Hadleigh Road Bridge are strikingly analogous in structure to certain englacial bands seen in Arctic glaciers.

II. THE NORTH-EASTERN SIDE OF THE RAILWAY CUTTING 1900 AND 1913 (plate 2, fig. 2).

This section extends between the two overline bridges and is generally parallel to the previous section. Its present height is in places 10 feet below its original height, owing to the excavations on the adjoining land. This section is the most complicated in the area. The structure of the section excavated in 1900 compares closely with that of the opposite side of the cutting, but the remaining half excavated in 1913 is quite different. In this portion of the section there are three asymmetrical curves corresponding in position to that on the opposite side of the cutting, each displaying on the longer limb evidence of exceptional directed and concentrated pressure.

Commencing at the Hadleigh Road overline bridge, boulder clay rests against, and partly includes, portions of Thanet Beds full of thrust-planes, the two formations resting against the limb of an anticline of London Clay. This anticline is followed by a striking sigmoid curve associated with large thrust-planes inclined at high angles from the top to the bottom of the cutting, this structure forming the exposed side of a truncated arch of London Clay. This second anticline is followed by, and is intimately associated with, the third one where the asymmetrical curve is seen to greatest perfection. One limb of the latter in its upper part shows a nipped-in lenticle of Red Crag associated with a puckered mass of London Clay. The three anticlines described, correspond in position to the simple asymmetrical curve on the opposite side of the cutting, the exceptional packing of the London Clay being due to the effect of pressure from another direction in the adjoining portion of the area. This structure can therefore be dealt with to better advantage at a later stage when the various directions of pressure and movement of the area as a whole are considered. Compared with other sections the following points seen in this section merit special attention.

- (1) The amount of transported Crag is greater in this section than on the opposite side of the railway cutting.
- (2) The central basins of the two sections correspond, but in this basin the lenticles of Crag have preserved their structure.
- (3) Boulder Clay occurs above the central basin as well as in the two basins adjoining the overline bridges at the ends of the cutting.
- (4) Very little gravel is seen in this section, whilst in the adjoining area there is a considerable development of gravel.

- (5) The line of section cuts diagonally across the axes of the anticlines as in the section on the opposite side of the cutting.
- (6) In plan, the lines connecting corresponding anticlines of the two railway-sections are not at right angles to the direction of thrust. This is a point of fundamental importance.

III. THE HADLEIGH ROAD SEWER SECTION, 1913 (Plate 2, fig. 3).

This section extends from near the junction of the London and Hadleigh Roads to the entrance to the Diesel Works (now Messrs. Vickers-Petters, Limited). The depth of the sewer varied from 4 feet to a maximum of 20 feet. The structure is shown in the section (plate 2, fig. 3) and the following points are of special importance:—

- (1) There is only *one* major asymmetrical curve of Reading Sands and of London Clay, but traces of the commencement of another occur near the junction of the two roads, and a minor disturbance occurs near the entrance to the engineering works.
- (2) The direction of pressure, as shown by thrust-planes, is nearly at right angles to that shown in the railway sections.
- (3) The amount of "tipped" London Clay is unusually small as compared with the amount seen on the longer limb of the "fold." Boulder clay occurs beneath the London Clay in the latter.
- (4) The amount of Red Crag seen is negligible.
- (5) A strong development of sand overlain by Chalky-Kimmeridgic boulder clay occupies the leeward basin, but elsewhere occurs only sparsely; moreover, gravels, such as occur in the central area, are for the greater part absent.
- (6) This section, which commences at 16 feet above O.D., displays the base of the Reading Sands *in situ*. The core of Reading Sands is the largest seen in the area.

IV. THE HADLEIGH ROAD HILL SECTIONS.

In order to understand these sections it is necessary to give a few particulars of the method of work. The excavations were commenced in the autumn of 1905 and continued at intervals until 1909, the result being the truncation of the hill and the formation of an inclined plane suitable for building purposes. The sections consisted of two series. The work proceeded at a rapid rate, as many as 200 men being employed at one time, but on three occasions a respite occurred, and there was ample time to study the sections in detail. The position of the

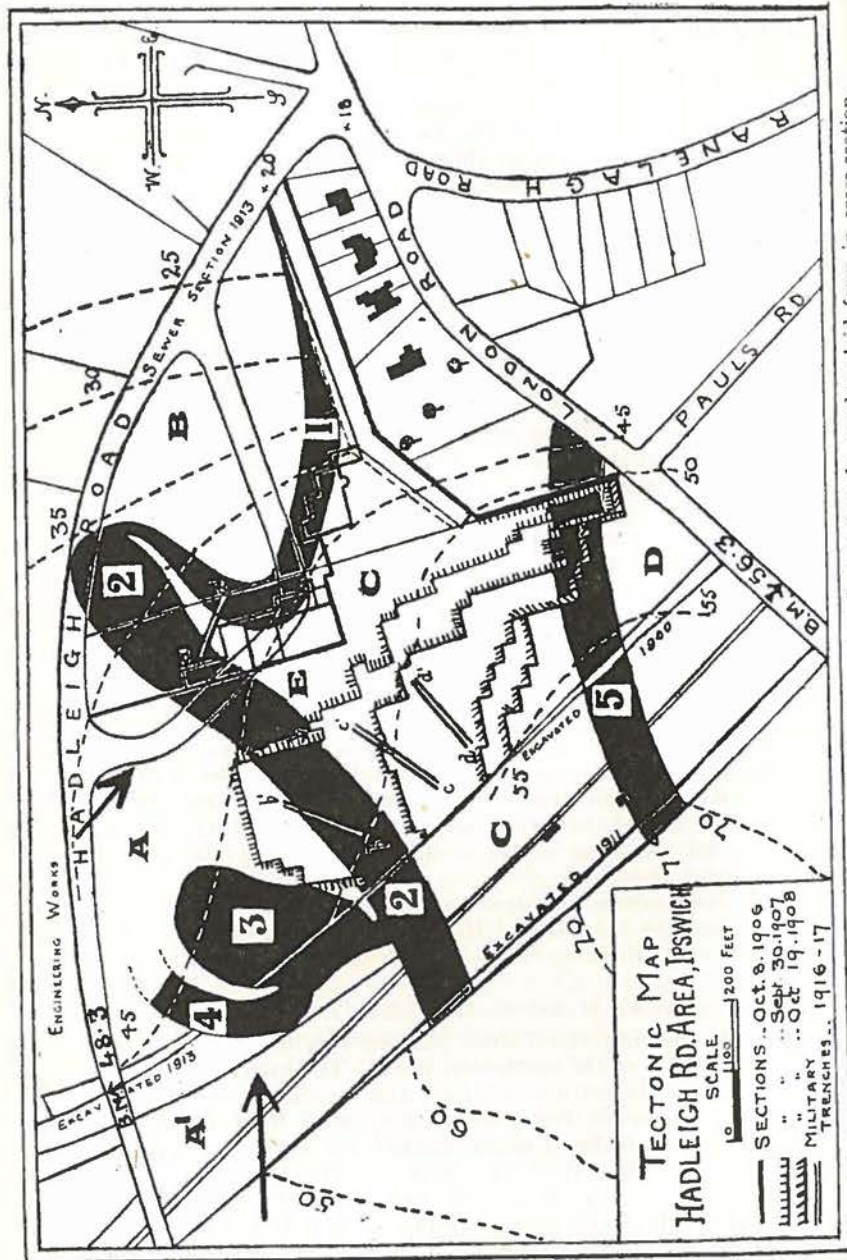


Fig. 23.—Black:—1, 2, 3, 4, 5:—Buried ridges of roche-moutonnée, or drumloid form in cross-section. A, B, C, D:—Portions of spoon-shaped basins. E: Area of Compression

lines of sections shown at these intervals are indicated on the map (fig. 23).

Fortunately these lines of section correspond very closely with critical parts of the tectonic structure. As, however, the details of the structure are numerous and to some extent perplexing unless a general idea of the structure as a whole has been obtained, a tectonic map has been prepared, reference to which will frequently be made in describing these sections (fig. 23).

This map shows the distribution of the series of domes and anticlinal ridges, numbered 1, 2, 3, etc., and of the basins already alluded to, the basins being lettered A, B, C and D.

It will thus be seen that the sections on October 8th, 1906, occupy the rim of the basin B.

The Sections, October 8th, 1906—The "rim" of basin B.

The early excavations in the easterly corner of the Hadleigh Road Area were in terrace-gravel. As the work proceeded, boulder clay was met with and proved to be a thick deposit of structureless clay associated with gravel and sand below, towards the rim of the basin, which occupied most of this part of the area. This clay is a continuation of that seen in the "sewer" section and the combined evidence proves that it has a steady rise southwards and occupies a basin-like area (fig. 24). On cutting through the boulder clay, disturbed masses of Crag and sand and gravel associated with London Clay were met with, and the structure was well-displayed in the sections seen on October 8th, 1906 (plate 3). These sections may be divided into two series: (a) a long section N.-S., parallel to the line of fence marked on the 25-inch map (fig. 23), (b) a series of sections N.-S. and E.-W., extending from the fence to the houses adjoining the London Road. The trend of the sections therefore differs from the previous ones described. At the junction between the two series a military trench was excavated in 1916 in a N.W.-S.E. direction (fig. 25 A-A').

Commencing with the "fence" section, the excavation showed the structure to be a long, low asymmetrical curve of London Clay with oval shaped masses of Crag above, the longer slope directed towards the north. The military trench (fig. 25 A-A') showed that the steeper slope passed into a graceful synclinal hollow, marked by alternate layers of crag, London Clay, sand, and gravel. The next series of excavations proved that this hollow was part of another asymmetrical curve, which was well displayed in two of the sections, the leeward side ending in a sharp curve and being associated with tip-structure.

We thus have evidence of two asymmetrical curves with an intermediate synclinal trough. The "fence" section links up

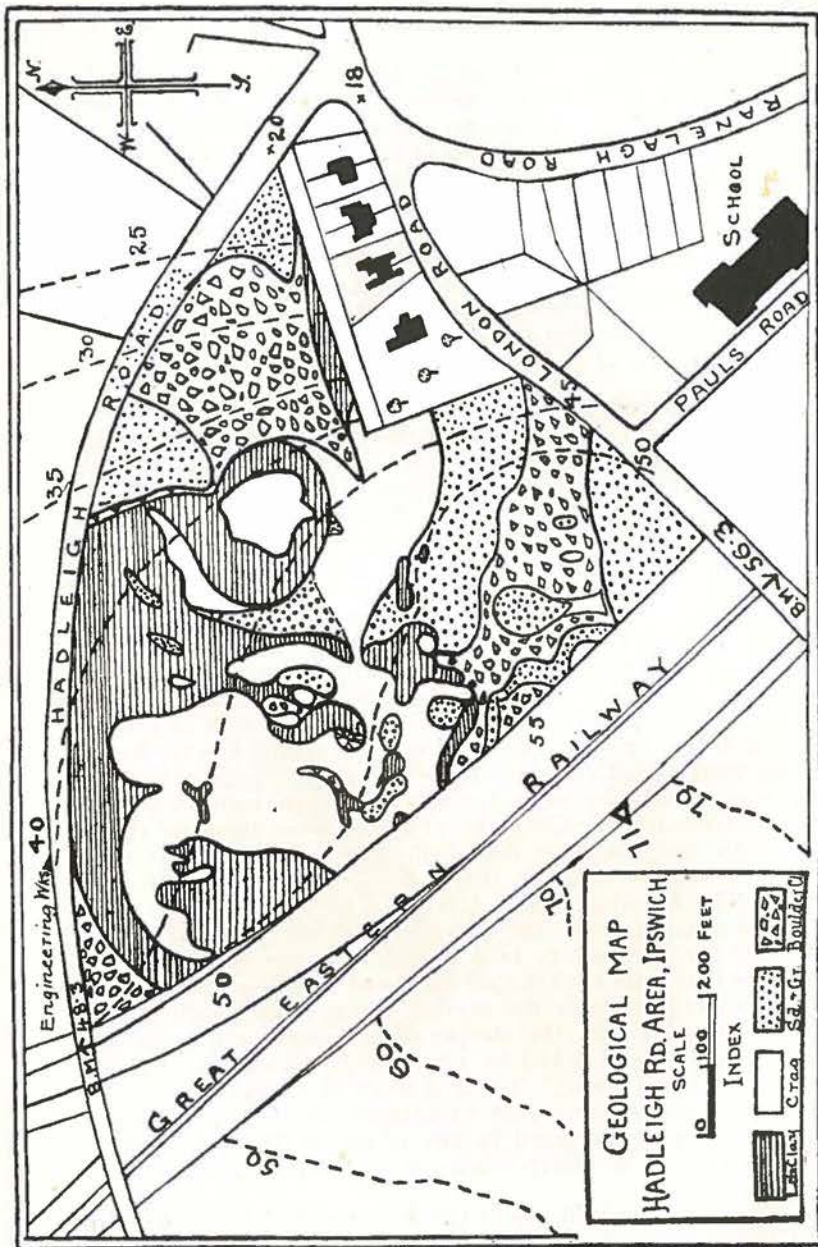


FIG. 24.—Geological structure of the inclined plane after the truncation of the hill in 1909. The radiating form of the transported Crag is a noteworthy feature, and is due to pivotal movement round a buried "spur" of Reading Sands. (1917).

with the part of the sewer-section on the exposed side of the core of Reading Sands. The respective levels of the London Clay prove a general rise of the sheets of transported material towards the south, that is, towards the more central part of the area. The strike of the thrust-planes in the sewer section and of the material forming the basin, point to a direction of movement approximately from the N.N.W. to N. The trend of the line joining the tip-structure or leeward sides of the main curves, on the other hand, is not at right angles to this direction, as one might expect, but is approximately in the same direction (see map, fig. 23, ridge 1).

The sections excavated along the upper platform of the 1906 excavations had the general characteristics of deposits on the leeward sides of the curves, and showed but little structure (plate 3, Nos. I.—VII).

The sections E.—W. gave evidence of a slight movement also from the west, which resulted in a rolling type of structure. The combined effects of the two directions of movement was the production of minor domes and basins.

The various sections just described prove the extension of London Clay continuously as a crescentic mass round the periphery of the area and a general sweeping inwards of the beds towards the more central part. The amount of Red Crag in these sections has definitely increased, and the long axes of the oval-shaped "boulders" of this deposit coincide with the direction of movement already deduced.

V. THE HADLEIGH ROAD HILL SECTIONS, SEPTEMBER 30th, 1907 AND 1917.

The area between the upper lines of sections, Oct. 8, 1906, and September 30, 1907 (fig. 23).

The geological map (fig. 24) shows a considerable deposit of Red Crag arranged in lobate form, radiating from a point near the middle of the adjacent railway embankment. The large amount of Crag here shown is in striking contrast to the small amount seen in the sections previously described.

The Red Crag (Pliocene) consists of two main masses occupying a large part of areas A and C, separated by a triangular-shaped area E, composed of sand and gravel, etc. (figs. 23 and 24). The area C, in addition to Crag, also contains a considerable deposit of coarse sand and gravel, the portion shown on the map, fig. 24, being only part of a wider spread now removed from the surface of the adjacent outcrop of Crag.

Details of the Areas A, C and E. (fig. 23).

(1) Area A.

Various sections prove that the Crag of this area rests in a basin of disturbed London Clay. The "nip-in" of the Crag

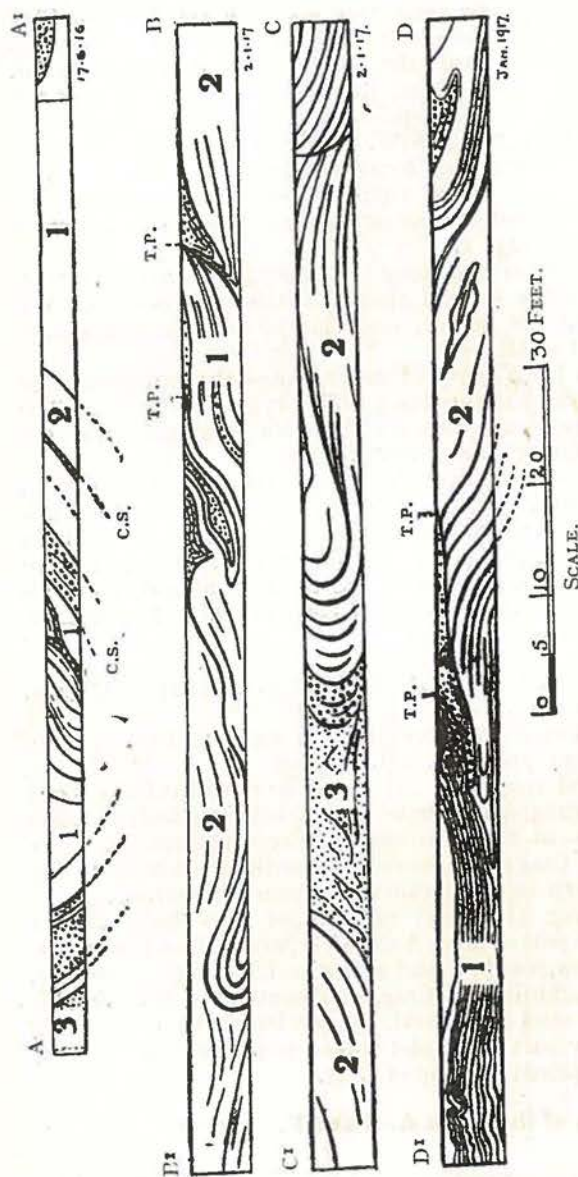


FIG. 25.—HADLEIGH ROAD AREA, IPSWICH.

Sections seen in four of the Military Trenches 1916-17. For position see Tectonic Map, fig. 23.

3. Glacial sands and gravels.
 2. Red Crag, both shelly and decalcified. Contains ironstone bands. Coprolites were common in some of the trenches, where disturbed Crag rested on London Clay.
 1. London Clay, with cement-stone (C.S.).
 T.P. = Thrust-Plane.

on two sides of the truncated anticline III. has already been shown in the Railway Section (plate 2, fig. 2). The two anticlines of London Clay shown in these sections also rise slightly and then pitch towards the centre of basin A, ultimately dying out in that direction, hence they are in the nature of domes. The large thrust-planes are seen "in plan" in the map of basin A. They take the form of a curve and change in direction from N.-S. to N.E.-S.W., the latter direction being shown in the sewer section of 1913. The adjacent deposits of Crag and London Clay also outcrop along this line (fig. 24).

Elsewhere the floor of the London Clay is rippled into minor hollows containing pockets of Red Crag.

The area A¹ seen in sections of the railway-cutting may be regarded as forming part of the basin A, the combined basins containing the domes 3 and 4.

A portion only of the lip of this basin, marked 2, can be followed.

Evidence for the continuation of this rim is seen in the two railway sections, on the one hand, and the "fence" and "sewer" sections on the other. Between the "fence" section and the lower lines of the 1907 sections evidence for the continuation of this ridge was seen in a large anticline of Crag excavated in 1907, analogous to that seen in the railway cutting, and sections of a similar kind, but on a smaller scale, were excavated nearer to the railway cutting in 1917.

The material excavated in 1907 from Basin A.

Much of the material extracted from this area consisted of Red Crag and London Clay, but towards the rim of the basin, owing to a rise in the level of the ground, about 10 feet of material possessing an interesting structure was removed. The beds consisted of lenticles of Red Crag and London Clay, associated with sand and gravel and overlain in places by bedded boulder clay.

Adjoining the railway cutting the included lenticles of London Clay had apparently been derived from the surface of the adjacent truncated dome of London Clay 3; whilst on the brow of the ridge 2 a section in a military trench showed disturbed lenticles of Crag and London Clay associated with thrust-planes (fig. 25 B-B¹ and fig. 23).

(2.) Area C.

(a) *The Crag adjoining the rim of the basin 1.* (fig. 23).

This area forms part of a central basin C, portions of which have already been described in the two railway sections.

One of the rims of this basin occurs along the line of the 1906 sections and is marked 1. The structure of the beds on the leeward side of the lower portion of this rim agrees with that

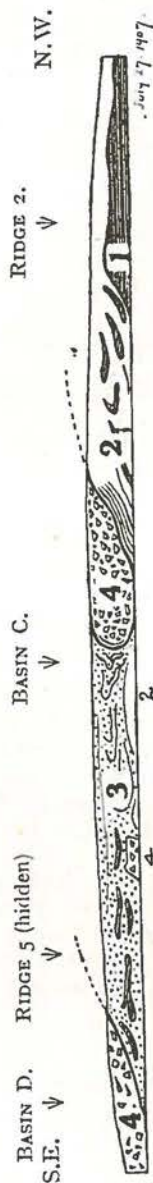


FIG. 26.—GENERALISED SECTION ALONG LINES OF SECTIONS, SEPT. 30, 1907 (see map, fig. 23). (Not to scale.)

4. Stiff boulder clay. At the south-east end this was of the Kimmeridgian type.
3. Glacial sands and gravels, contorted in places, and containing thin lenticles of transported London Clay which appear horizontal, but which dip when viewed at right angles. Irregular patches of boulder clay common. Flints derived from the chalk, numerous. Thanet-flints were also occasionally found.
2. Red Crag both shelly and decalcified. The Crag was associated with lenticles of London Clay and occasional patches of boulder clay. The Crag also occurred as oval-shaped masses, which were also associated above and below with thin strips of boulder clay.
1. London Clay, marking the crest of Ridge 2, near the railway line.

[For sections below the base-line of this section see figs. of Military Trenches C-C₁, D-D₁, of Fig. 25. These sections, however, are at right angles to Fig. 26.]

seen near the rim 2 and included "boulders" of Red Crag dipping down towards the basin C. In addition to this, the Crag and London Clay also rose towards the embankment to the east of the area marked by residences, proving the continuation of the ridge in that direction.

As regards the upper deposits adjacent to the ridge 1, the marked absence of structure seen in the upper line of sections in 1906 proved to be a general characteristic of the Crag in adjacent parts of the area.

(b) *The sand and gravel.*

The deposit of sand and gravel occurring in this area C is similar in structure to that seen in the Railway Section in 1911, and the rim I of basin B.

The chief characteristics are as follows:—

- (1) The gravel contains pebbles derived from various sources, both local and extra-local. Flints were very numerous, small boulders containing Jurassic fossils, and a mass of "Pudding-stone," whilst green-coated Thanet flints were occasionally seen. The suite of rocks was therefore similar to that seen in the boulder clay.
- (2) Intercalated in the sand and gravel were strips and lenticles of London Clay analogous to the deposits described in Bolton's sand pit. Ferruginous and shelly Crag and "blocks" and patches of boulder clay also occurred. The beds had a bedding peculiar to themselves; in places the lenticles of London Clay were horizontal, but usually the bedding was extremely variable. Cross-bedding, as seen in water-deposited material was, however, rare. In places the beds were contorted.
- (3) This deposit thinned out towards the rims of the basin C and was thickest in the half of the basin adjoining the rim 5 (figs. 23 and 24).

(c) *Generalised section between the two lines of sections, Sept. 30, 1907.*

The diagrammatic section (fig. 26) between the two lines of excavations (1907), shows the arrangement of the gravel in a direction N.W.-S.E., and its association with the Crag towards the rim of the basin C.

(3) *Area E (fig. 23).*

The area E occupied the centre of the Hadleigh Road Area, and is of peculiar interest.

It consists of a bedded series of London Clay, Crag and sand and gravel which occupy a basin of London Clay between the ridges 1 and 2, the beds being arranged in a pseudo-syncline (fig. 25 A-A').

The strike of the beds was approximately N.E.-S.W. This syncline is pinched out towards basin B, and widens towards basin C, the extension in this direction being shown during the 1907 excavations. In form it is analogous to portions of the pinched-in basin A, but is pinched in the opposite direction. Moreover, the arrangement of the beds suggests deposition in a hollow associated with thrust.

A further continuation of these beds towards the basin C in a section seen in 1907 showed this series of beds inclined in two directions, the beds dipping towards the north and west, recalling the inclined strips of Crag and London Clay seen in the railway section in 1911.

VI. THE HADLEIGH ROAD HILL. SECTIONS OCTOBER 19th, 1908.

The area between the upper lines of sections September 30, 1907, and October 19, 1908 (fig. 23).

The material excavated in this area consisted of two main series of deposits:—

- (a) Sand and gravel, etc., adjoining the ridge 5.
- (b) Red Crag with some sand and gravel and a little boulder clay nearer to the ridge 2.

(a) Sand and gravel.

Along the lower lines of section 1908, bedded boulder clay was met with, overlying and partly incorporating portions of the sand and gravel. This bedded boulder clay was part of the same mass exposed in the adjacent railway cutting, and proved the rise of the deposit from the railway line towards the basin C. The absence of the gravel beneath much of the lower boulder clay in the railway section, and its strong development in basin C proves an upward fanning out of this deposit towards the N.E. and recalls the structure seen in similar deposits in the section of 1911. (plate 2, fig. 1).

(b) Red Crag.

The Red Crag adjoining the ridge 2 also dipped towards the railway line. The adjacent railway section showed the Crag resting on a "mound" of Reading Sand, the surface of which rose towards the basin C.

The Crag there seen is therefore part of the same mass seen in the railway sections. Sections seen in two military trenches showed the association of Crag and London Clay, accompanied by thrust-planes (fig. 25 C-C' and D-D').

The upper line of sections 1908.

The remainder of the sections were in boulder clays and their associated gravels. Intercalated masses of gravel in the lower part of the bedded boulder clay were well shown in the

sections of 1908. Above the bedded boulder clay, Kimmeridgic boulder clay occurred as an isolated mass, the two being separated by chalky gravel. A second outcrop of the upper boulder clay was again met with along the adjoining ridge.

The heights above O.D. of the beds showed, as before, a rise towards the basin C and a wrapping of boulder clay over the sand and gravel.

The ridge 5 and basin D (fig. 23).

The excavations of 1908-9 in the corner of the area adjoining the London Road Bridge and the subsequent mapping proved the continuation of the crest of the curve seen in the railway sections, as a ridge marked 5. Confirmation of this has recently been seen by Mr. Guy Maynard (1925). Along the crest of the ridge the boulder clay was very thin and in places was cut through revealing the underlying Crag flanked by boulder clay. Much of the surface of the boulder clay of basin D was covered by sand and gravel (fig. 24), but an outcrop of Kimmeridgic boulder clay was sufficiently well-exposed to prove the existence of the ridge 5 with a similar structure to the truncated asymmetrical "fold" seen in the railway section of 1900.

III. Tectonic Features displayed in the Hadleigh Road Area.

A. TYPES OF STRUCTURE.

i. The Drumloid Curve or fundamental form.

The undisturbed core.

In the Hadleigh Road Area the surface of the outcrop of the Reading Sands beneath the disturbed deposits has been moulded into a series of asymmetrical curves resembling small roches-moutonnées, and upon this "rippled" foundation the disturbed local beds have been arranged over the undisturbed "cores," producing a series of ridges, domes, and spoon-shaped basins. Upon this surface a later series of beds has been deposited, consisting of sands and gravels intercalated with portions of London Clay and Red Crag, and overlain by boulder clays, the result being an infilling of the basins and the formation of a low hill.

The asymmetrical curve which forms the dominant feature of the structure of the disturbed beds is analogous to the drumloid curve developed in ice when passing over prominences.

*Traced across a "core" the local beds, as seen in longitudinal section, occur in definite stratigraphical succession, London Clay being overlain by Red Crag, but the internal structure of these beds differs markedly on each of the two limbs of the curve. The sections show that the complete structure is also composed of two superimposed masses, the lower one, composed of London Clay, being overlain by a later deposit of

Red Crag forming a curve of greater amplitude and length, and with altered gradients on the two limbs of the "core." Therefore, this type of structure is essentially different from the simple asymmetrical folds due to mountain building movements, the latter consisting of two parts—an arch and a trough mutually dependent on one another.

ii. The two parts of the Drumloid Curve.

(a) *The Iceward limb of the anticline.*

The iceward, or longer limb of the anticline has been directly exposed to pressure. This is shown by the development of thrust-planes associated with contortion and strain-slip cleavage in the London Clay. The effect of pressure on the Red Crag is shown both externally and internally, the former by the arrangement of oval-shaped lenticles, and the latter by the presence of fragments of resistant shells, such as *Neptunea*, which are broken *in situ* without the fragments being much displaced. Exceptional pressure is indicated by overthrust and inversion. This limb of the anticline is constituted of superimposed lenticles of London Clay and is of composite structure throughout. This is the dominant part of the structure.

(b) *The Leeward side or "tip-slope."*

The steeper or leeward limb of the anticline is marked by a graceful curve dipping sharply over the mound of Reading Sands. The outline of this curve which marks the "protected" side of the drumloid curve is well shown in the London Clay by bands of massive cement-stone. Wedges of material composed of re-arranged London Clay, with nests of gravel inclined against the arch of London Clay, form a small tip-heap structure, which is one of the chief characteristics of this limb. The "boulders" of Red Crag forming the upper series suggest movement *en masse* over the crest, and gravitational slide on the leeward side of the curve. These "boulders" are frequently associated above and below with strips of boulder clay.

iii. Over-rolling or switchback type of the lower duplicated folds.

Sections displaying consecutive cores suggest that an over-rolling type of motion has taken place. The formation of a roche-moutonnée of London Clay ceased on the completion of suitable gradients on the two limbs of the anticline. The upper surface of a completed core then formed a glide-plane over which more London Clay was transported onwards, until arrested in turn by another mound of Reading Sands, when the process was repeated, thus resulting in the formation of another roche-moutonnée (plate 2). It therefore follows that the order of formation of those consecutive roches-moutonnées followed the

progress of the movement. A noticeable feature is, that a much larger amount of material occurs on the iceward limb than on the leeward; in some cases this is abnormally the case, as in the Danish and American sections described by the author; in these sections there is also an exceptional development of large thrust-planes.

The formation of the succeeding superimposed structure of Pliocene material is intimately associated with the London Clay roche-moutonnée, but has involved two factors of structural importance:—

- (a) The formation of gradients differing in amount from those of the lower deposits.
- (b) The incorporation of Red Crag from higher levels in the district, thus involving a greater amount of vertical displacement.

The crests of the curves when composed of Red Crag are evidence of the anticlinal structure and form a useful index to the position of the axes and tops of the curves when they are only partially exposed.

iv. Other types of structure.

The upper series of deposits represent the second and final phase in the production of the structure of the disturbed deposits. This material consists of two well-marked series which have been deposited in the basins formed by the underlying disturbed local deposits. The two series of beds are as follows:—

- (a) A lower series of sands and gravels associated with lenticles of London Clay and Crag. When occurring on the iceward crests of the anticlines these beds are associated with minor thrust-planes which are beautifully developed, but as a rule these beds are typically shown in the "basins" and display individual bedding of a distinctive character.
- (b) An upper series consisting of two types of boulder clay:
 - (i) A lower sandy bedded boulder clay, associated below with the sands of the former series and separated by chalky gravel from the upper boulder clay.
 - (ii) The Upper or Kimmeridgic boulder clay, which is the only unbedded deposit of the area. It is the usual stiff bluish clay of the district, containing much Jurassic material and well-rounded erratics, the matrix consisting of Kimmeridgic material.

B. MOVEMENT.

i. Two chief directions of pressure.

The maximum amount of pressure, as evidenced by the thrust-planes, occurred in the north-west part of the area in the neighbourhood of the Hadleigh Road Bridge.

There are two chief directions of pressure :—

- (a) One from the west, which produced the large thrust-planes associated with dome 3 (fig. 23).
- (b) One from the north-north-west to north, which produced the small thrust-planes seen in the sewer section and the general sweeping inwards of the deposits towards the south.

The two directions of pressure were therefore approximately at right angles to one another. Each pressure was dominant in definite parts of the area.

If a line, for example, be drawn across the map (fig. 23) from the entrance of the engineering works to the corner of basin D, the area is divided into two zones each of dominant pressure. Between this line and the railway cutting the dominant pressure was from the west, whilst in the other half of the area the dominant pressure was from the north-north-west to north.

On the other hand, each zone has been influenced to a lesser degree by pressure approximately at right angles to the direction of dominant pressure.

For example, the area affected by dominant pressure from the west has been influenced to a lesser degree by pressure from the north-north-west to north, and the effects of this latter pressure are seen in two ways :—

- (1) The lesser pressure has produced minor folds or ripples in the London Clay and associated beds.
- (2) The crests of the ridges have been deflected, the lesser pressure appearing to exercise a marked influence on the direction of the lines of ridges, and the leeward deposits of the drumloid curves.

In the geological and tectonic maps (figs. 23 and 24), for instance, a portion of the rim of basin B shows tip-structure towards the east, whilst the dominant pressure was from the north.

Again, on the leeward side of ridge 2 of basin C adjoining the railway cutting, the dominant pressure was from the west, but the tip structure is towards the south-south-east.

The same phenomenon occurs in the rim 5 of basin D.

In the case of rim 1 of basin B the dominant pressure was from the north, producing the north-and-south anticlines, but movement at approximately right angles to this direction is indicated in the sections of plate 3.

The dominant pressures appear to reach a median zone of relative equilibrium in the basin C, now defined on the geological map by the deposit of gravel (figs. 23, 24).

These facts lead to the conclusion that each of the two dominant pressures was associated with tension at right angles.

Hence each pressure led to movement in two directions :—

- (a) Movement in the direction of dominant pressure and associated with thrust-planes.
- (b) Movement at right angles to (a), the result of tension being marked by an absence of thrust-planes, but an association with flow or tip-structure.

The tectonic map (fig. 23) shows two areas which have been subjected to exceptional pressure. These areas are V-shaped, the apex of the V occurring in opposite directions. One of these areas occurs near the railway line between ridges 3 and 2; the other occurs in the pinched-in area E.

The area E is of especial interest :—

- (a) It marks a point where lines drawn in the two main directions of pressure would meet. (See fig. 23—continue the two arrows.)
- (b) It represents a pivotal point of movement. The beds in this area form a "pinched synclinal structure."

ii. Relative rates of movement both vertically and horizontally—Resistance to movement.

(a) *Horizontal movement.*

The geological map shows that the main mass of London Clay extends from the railway cutting adjoining the Hadleigh Road Bridge, round the periphery of the area bounded by the Hadleigh Road, and terminates in the ridges 1 and 2 (figs. 23 and 24).

We are justified in regarding this spread of London Clay as having been laid down at approximately the same time and that the two ridges are contemporaneous.

The source of supply of the London Clay and Crag deposits was undoubtedly from the neighbouring outcrops to the west of the area. It therefore follows that the beds moving round the periphery of the area must have travelled at a greater rate than those nearer the railway cutting.

The result of different rates of movement coupled with a difference of direction of pressure has been the production of the lobate structure seen on the map, and the sweeping inwards of the various deposits (fig. 24).

The pivotal point appears to be in the area E already mentioned.

(b) *Vertical movement.*

A study of the various sections, especially those of the railway cutting, leads to certain conclusions regarding movement of superimposed beds.

The stranding of London Clay to form the drumloid curves points to cessation of movement, which first commenced when the cores of Reading Sands were reached. The passage of material over these cores points to a gradually increasing rate of move-

ment of the overlying beds *pari passu* with the formation of suitable gradients, and this is supported by a consideration of the geological formations incorporated in the deposits. The Upper or Kimmeridgian boulder clay has been derived from outcrops many miles distant, the Crag from outcrops in the neighbourhood (about 100 ft. above O.D.), and the London Clay from outcrops in the immediate vicinity.

(c) *Resistance to movement.*

Resistance to movement is shown fundamentally by the Reading Sands in the railway section (plate 2, fig. 2). This section shows the formation of the drumloid curve over Reading Sands and the ploughing of the leeward deposits into a bank of this sand, which effectually prevented further motion of the basal deposits. The effort to overcome this resistance led to the formation of thrust-planes on the exposed side of the "fold," and the building-up of thrust deposits ultimately led to the formation of a gradient which resulted in an increased rate of movement of the upper material. Rate of movement in a horizontal direction varied with the amount of resistance. Hence a "core" acted as a fulcrum of horizontal as well as vertical movement and led to pivotal motion of the associated deposits.

iii. *Mechanics of Structure—Directions of thrust as the resultant of forces.*

A study of the geological and tectonic maps shows that the trend of the outcrops of the deposits may be arranged into two series:—

- (a) Those which occur on the exposed sides of the rochemoutonnée.
- (b) Those which occur on the protected or leeward sides.

The former are most clearly displayed in basin A, the latter in the central basin C:—

- (a) The lines of outcrop on the exposed side of the rochemoutonnée of basin A are at *right angles* to resultants of the two somewhat varying directions of dominant pressures. Hence they take the form of curved lines which represent graphically the relative increase or decrease of each of the two dominant pressures when traced across the area from the railway line to the Hadleigh Road.

The outcrops in basin A belong to the *earlier* series of disturbed deposits, and consist of London Clay and Red Crag.

- (b) The outcrops of the *later* series of deposits of sand, gravel and boulder clay, occupying a large portion of basin C are, on the other hand, in the *same direction*

as the resultant of the two general directions of pressure. Moreover, there is a marked absence in these deposits of thrust-planes of the type previously described.

On the other hand, the deposits forming the rim of basin C are associated with thrust-planes, and this is due to factors which are connected with the progressive infilling of this basin, and the extension of the crest of the fundamental drumloid curve due to the accumulation of material on the two limbs of the curves. This leads to the formation of an inclined plane on the flattened dome and an increase of the surface exposed to pressure.

The area E is one of especial interest:—

- (1) It occupies a central position of pivotal movement.
- (2) Its position is such that if two lines representing the directions of the two dominant pressures be drawn across the area they converge in the centre of the area E. It follows, therefore, that a belt stretching from the area E along the median axis of the basin C, marked by sand and gravel, represents a zone of tension.

iv. *Domes and Basins. Reasons for their formation.*

The various factors which have combined to form the structure may be briefly summarised:—

- (1) Two directions of dominant movement associated with pressure, the movement from the north-north-west to north deflecting that from the west.
- (2) Differential movement, the greatest movement occurring at the periphery of the area marked by the Hadleigh Road. This led to the formation of lobate-outcrops.
- (3) Obstruction to movement resulting from an outcrop of Reading Sands, of "horse-shoe" shape. This outcrop was moulded into two main ridges (resembling roches-moutonnées of sand) and four basins, one at each corner of the triangular shaped area and one in the centre.
- (4) The transporting of stratified bands of coloured material from outcrops to the west and the moulding of this material on the limbs of the folds.

The order of formation of the structure was as follows:—

- (a) "London Clay" phase:—
 - (1) The formation of the two ridges 1 and 2, forming the leeward rim of basin C.
 - (2) The formation of the ridge 5, between basins C and D.
- (b) "Red Crag" phase:—

The deposition of Red Crag on the limbs of the "folds."
- (c) Infilling of the basins by mounds of sand and gravel,

strips of London Clay and Crag, and finally by boulder clay.

The centre of deposition occurred in basin C which ultimately became the highest portion of the hill on the completion of the structure.

Associated with the deposition of boulder clay are the Thanet Beds already described in the railway section adjoining the Hadleigh Road bridge. These can only have been derived from the floor of the valley and point to progressive excavation, leading to an inversion of the succession.

v. Movement round a Spur.

The outcrop of the Reading Sands beneath the disturbed deposits formed a pre-glacial feature, and occurred as a spur on the side of the Gipping Valley. Its original height cannot be determined accurately, but appears to have been not much greater than approximately 40 ft. above O.D.

The presence of the adjacent deep glacial channel is of much interest. It extends nearly a mile across the valley, and its base is 80 ft. below O.D. near the Hadleigh Road Area, or about 120 ft. below the platform of the disturbed deposits. As this channel is filled with glacial deposits consisting chiefly of re-arranged boulder clay, the channel must have been in existence during the period of formation of the disturbed deposits. The presence of such a channel would readily explain the deflection of the movement from the west, which the disturbed deposits prove to have been down the side of the valley.

vi. Relative change of level of the beds.

The general levels (O.D.) of the disturbed beds are shown in the appended table (p. 205).

With the exception of the Thanet Beds, all the disturbed deposits occurring in the Hadleigh Road Area have been derived from outcrops occurring at higher altitudes. This downward movement has been replaced by an upward movement, where obstruction was met with, but was followed by a downward movement on the leeward sides of the "folds." The highest altitude finally attained by the transported material was 66 ft. above O.D., or 70 ft. above O.D. in the summit of the railway cutting.

The relative positions of the disturbed beds show that there has been a progressive change from the switchback mode of progression to general movement upwards which culminated with the infilling of basin C.

The gradual evolution of the structure is due to a steadily decreasing rate of movement of the ice and débris over the whole area.

GENERAL LEVELS (O.D.) OF DISPLACED BEDS IN THE HADLEIGH ROAD AREA :—

		Hadleigh Road Area		Level <i>in situ</i>	Amount of Displacement	
		Level O.D.		Level O.D.	Upward	Downward
		Maximum	Minimum			
1.	Thanet Beds	42	32	16	16 to 26	—
2.	Reading Beds	38	32	16-45	Upper surface removed	
3.	Oldhaven Beds	32+		45	—	13
4.	London Clay	50	32	45-85	18+	13+ to 53
5.	Red Crag	50	32	85-100	18+	53+

C. TOPOGRAPHICAL FEATURES DUE TO THE ARRANGEMENT OF GLACIAL DEPOSITS.

i. Evolution of land-forms.

The accumulation of glacial material on the platform of Reading Sands has resulted in the formation of a low dome-shaped hill, the change in level being approximately from 40 ft. to 70 ft. above O.D.

The contours therefore mark this hill as a glacial feature, and the radiating form of the contours when followed west of the railway line indicate the extension of the glacial feature in a direction N.E.-S.W. to the neighbourhood of Crane Hall, a total distance of about half a mile. The average width of the hill is approximately a quarter of a mile.

The trend of these contours indicates the influence of movement from the west, and is in accordance with the evidence previously given.

It is entirely owing to the composite nature of the disturbed deposits that the evolution of the structure could be followed. If, however, the whole of the material had been of the same character it seems reasonable to assume that the same course of events would have taken place, but under modified conditions. The evolution of the structure would, in that case, have been extremely difficult, if not impossible, to follow. For example, sand-hills of glacial origin are extremely common in the Buildwas area of the Severn Valley, whilst drumlins composed essentially of clay have been described from various areas, and disturbances in chalk have been described in the Royston area. How far the present investigation throws light on these questions is indicated in the subsequent parts of this thesis.

The Hadleigh Road Hill has been shown to have many features in common with drumlins, and this resemblance would

have been still more marked had the outcrop of Reading Sands been an isolated feature.

There is also a strong resemblance in structure between this feature and the isolated hills of hummocky drift of the Norfolk Coast.

ii. Drainage and conditions of deposition.

The main drainage of the Gipping Valley was by means of the adjacent glacial channel, the deposits in which are characterised throughout by deposition in running water. The effects of this channel are not seen in the disturbed area, but a small superficial channel occurs in basin D which, however, is of later date. The order of deposition of the disturbed deposits is as follows:—

- (1) *An early phase* marked by the stranding of lenticles against and over obstructions.
- (2) *A later phase* of deposition of numerous layers of bedded material composed of Crag, sand, London Clay, and strips of boulder clay. The layers are often only an inch in thickness, and each layer preserves its individuality and is uncontaminated by the beds above or below. These deposits are characteristic of the basins and show an entirely tranquil mode of deposition. This type of bedding extends to the base of the upper Kimmeridgic boulder clay.
- (3) *A final phase* marked by the deposition of the upper boulder clay. This clay is unstratified, and shows little sign of structure either on the exposed or protected sides of the underlying deposits.

IV. Analogous Effects Due to Modern Ice-Action as Exemplified in Greenland and Spitsbergen.

i. Bedding and material in glaciers.

The presence of englacial material in glaciers in the form of débris-bands is a common characteristic of the glaciers in Greenland and Spitsbergen. These débris-belts are usually confined to the lower part of the ice and are more abundant at the sides of the lobes than in the centre. The thickness of the belt depends largely on the hardness or softness of the rocks framing the bed of the glacier. In Greenland it is confined to the lower 50 or 75 feet, and is rarely beyond 100 feet, the extreme thickness not exceeding 150 feet. In the Nordenskiöld Glacier of Spitsbergen, where the floor is composed of hard resistant rocks, the belt is about 25 feet thick.

The dirt-bands are arranged parallel to the floor of the glacier and are composed of rapidly changing layers, lenticular in form, which dovetail into each other. Much of the material consists of silt-like laminæ which curve round included

boulders. The layers also show faulting, drag and thrust phenomena.

The lower discoloured division may consist of one great stratum, but oftener it consists of several large bands each divided into minor layers grading down to delicate laminations each a fraction of an inch in thickness. In the upper part of this zone lenticular heterogeneous masses of boulders, gravel, or drift sometimes occur.

Above the lower zone of discoloured ice is a mass of pure ice of varying thickness.

ii. Thrust-planes in Ice.

The streaky arrangement of the lower layers is due to thrusting. Innumerable thrust-planes occur, but the major thrusts are between the dirt-bands and the purer layers of ice. Thrust-planes in ice appear to be due to the pressing of ice against obstructions, the thrusting taking the line of least resistance and forming flutings and grooves with slickensided faces on suitable material. Obstructions to the flow of ice are various, but may be divided into two classes: (a) irregularities in the bed of the glacier, and (b) morainic débris on the flanks of the ice due to the melting out of the material forming the englacial layers.

The angle of inclination of the thrust-planes varies with the amount of pressure and form of the obstruction. The thrust-planes are developed on the iceward slope of the obstruction, on the side directly exposed to pressure.

Sometimes the whole of the ice is riddled with thrust-planes and imbricate-structure is developed. In other cases the basal layers, filled with englacial material, form the sole of a thrust over which the purer layers of ice pass along curved thrust-planes, as in the Sven glacier of Spitsbergen.

iii. Behaviour of ice passing over prominences.

In the case of a low boss of rock forming an obstruction, the laminæ in the ice commence to rise on the exposed side and curve upwards with a low inclination, arch over the brow of the obstruction and then curve down more steeply on the leeward side, the whole forming a graceful curve, the higher laminæ naturally forming the longest curves. Towards the lower part of the lee slope, some of the curves run backwards to near the rear of the underlying material, due to the upper beds moving more quickly than those below. This symmetrical curve is the "*Drumlöid curve*."

Where the obstruction is greater, as in the case of a nunatak, the ice is much compressed on the exposed side, thrust-planes are formed and the surface of the ice rises considerably above

its average level, whilst the lee-side is heavily crevassed. On the melting-out of the ice, the inclined structure on the thrust-side may be to some extent preserved in the morainic matter, as in the Cora glacier of Spitsbergen. The rising upwards of basal material along thrust-planes has been noted in the case of the Von Post glacier of Spitsbergen, and has already been described by the author in the section at Mason's Pit.

iv. Contortion of Ice.

Ice, when subjected to pressure, may also develop contortions on either a small or a very large scale. Dirt-bands associated with thrust-planes are sometimes intensely foliated and contorted like gneiss. Contorted ice filled with englacial material may also occur on the leeward slope of a boss as in the Ebba glacier of Spitsbergen.

Another type of contortion is analogous to the flow of a plastic body. In the Paula Glacier of Braganza Bay, Spitsbergen, the contortions are on a large scale and assume long, oval-shaped, lenticular curves in ice filled with detritus.

Highly contorted dirt-filled ice also occurs in the Négri glacier of Spitsbergen.*

v. Movement of ice under pressure.

The types of movement in a body of ice are various and complex. Forbes long ago proved that the various rates of movement on the surface of a glacier assumed curves when the points of equal rates of movement were plotted on a map.

When two currents of ice of varying volume and rates of movement converge, a mutual adjustment of movement occurs, but the surface moraines maintain their individuality. Cases occur, however, where the lower and upper ice have had different directions of flow. Where directed concentrated pressure occurs, other types of movement may result.

When ice, for example, meets with an obstruction it takes the line of least resistance, but, under exceptional cases, pressure may be developed and thrust-planes formed in the effort to overcome the obstruction. This type of movement is seen to best advantage in the superficial névé ice, and in such cases the two types of movement are as follows:—

- (1) Movement in the direction of pressure along thrust-planes, associated with contortion and imbricate structure.
- (2) Irregular movement or slide at right angles to the direction of pressure, associated with tensional phenomena, such as the formation of crevasses.

Analogous movements to these have already been described as occurring in the Hadleigh Road Area.

* Helge Backlund. *Mesure d'un Arc de Méridien au Spitzberg, 1899-1901.*

vi. Experiments illustrating ice-movements.

Experiments carried out for the purpose of illustrating ice-movement have frequently been made. In all the well-known cases a plastic medium has formed an important part of the experiment. Such a medium has usually been made to pass against and over an obstruction, and the resulting curves have been compared with the phenomena seen in ice under similar circumstances.

The problem, however, is very complicated, and the actual motion of ice by experimental methods cannot be adequately demonstrated by a viscous quasi-fluid, as ice is an elastic-rigid crystalline solid, and moves by shear. A viscous body cannot therefore represent the exact behaviour of ice when meeting with obstructions. On the other hand, there is a striking resemblance between the structure seen in ice on the leeward side of an obstruction, and the experiments of Professor Sollas* and E. C. Case.

The most fruitful line of investigation would rather appear to be actual observation over a prolonged period of small glaciers like those occurring in Spitsbergen, such as the Sven and Ebba Glaciers at the head of the Ice Fiord.

V. Analogies between the structure of the Hadleigh Road Area and certain modern glaciers.

a. The fundamental curve (drumloid curve) seen in the Hadleigh Road sections is similar in outline to those seen in Arctic glaciers, both in Greenland and Spitsbergen, and is associated with the movement of ice over prominences.

b. The peculiar bedding assumed by englacial material in Arctic glaciers, whether horizontal or inclined, is strikingly similar to that of the Hadleigh Road beds, allowing for a rearrangement of the layers of separate material due to the conversion of interstitial ice to water.

c. The arrangement of englacial material in the Ebba glacier of Spitsbergen, consisting of banded lower layers with patches of interstitial gravel above is similar to some of the minor basins in Hadleigh Road.

d. The presence of thrust-planes in the upper ice and a major glide-plane over the upper surface of the lower englacial material as seen in the Sven glacier of Spitsbergen is analogous to the structure seen in the railway sections, except that in the Sven glacier the upper ice is pure. In other glaciers the analogy is well-nigh perfect, as the upper inclined layers of ice arranged along thrust-planes are full of englacial material.†

* *Quart. Journ. Geol. Soc.* 1895, pp. 361-368. The later experiments on "Pitch-Glaciers" by Prof. Sollas, reproduced in a striking manner the structure of the Hadleigh Road Railway sections.

† *Quart. Journ. Geol. Soc.* 1898, pp. 197-227, Pl. xiii., fig. 1. Prof. E. J. Garwood's photo of the Ice-Plough Glacier is almost identical in principle with the structure seen in the Railway section, Plate 2, fig. 1 upper part towards the N.W. end.

e. Nevertheless, disturbed drift sections often show a development of structure on a scale not to be paralleled in size with that to be now seen in Arctic glaciers. The clearness of the evidence of drift sections is also not confined to marginal deposits of ice-sheets, and hence most valuable evidence is available supplementary to investigation of modern glaciers.

VI. Summary.

1. LITHOLOGY OF DEPOSITS.

The hill is composed of glacially-disturbed material derived from five local outcrops. These beds rest upon an outcrop of Reading Sands. The beds incorporated consist of Thanet Beds, Reading Sands and Clay, Oldhaven Beds, London Clay and Red Crag, whilst the upper or later deposits consist of sand and gravel and boulder clay containing material from further afield. The lithology of each of these deposits is characteristic and distinctive.

2. STRUCTURE.

The surface of the Reading Sands has been moulded into two main ridges of crescentic outline, resembling roches-moutonnées in transverse cross-section. With these ridges are associated four basins, one at each corner of the triangle and one in the centre.

Upon this rippled foundation the transported lenticles have been moulded in orderly sequence: first London Clay, above this Crag, and finally sand and gravel with boulder clay, resulting in the infilling of the basins and converting the central basin into the crest of the hill.

The asymmetrical curves over the "cores" of Reading Sands are described as "drumloid curves." The exposed limb of each fold is associated with thrust-planes, whilst the protected or leeward limb is associated with tip-structure. The latter phenomenon is also produced laterally to the main directions of pressure.

3. TECTONICS.

(a) Movement.

There are two main directions of pressure, one from the west, the other from the N.N.W. to N. Each of these pressures is dominant in the two halves of the area, the former in the part adjoining the railway cutting, the latter in the neighbourhood of the Hadleigh Road. Each dominant pressure (longitudinal) was accompanied by tensional movement (lateral) at right angles, the latter favouring the production of tip-structure.

The two main directions of pressure are approximately at right angles to one another.

(b) Relative rates of movement.

Differential movement has taken place both vertically and horizontally.

(1) *Vertically.* The stranding of lenticles of material against obstructions has led to cessation of movement below and increased movement of the overlying beds on the completion of suitable gradients.

(2) *Horizontally.* Movement round the periphery of the area was quicker than that nearer to the railway embankments. The result has been the formation of lobate outcrops.

(c) Mechanics of structure.

The outcrops of the lower deposits on the exposed limbs of the folds are at right angles to the resultants of the two pressures.

On the other hand, outcrops of the later deposits of sand and gravel and boulder clay in the median axis of basin C, are in the line of direction of the resultant of the two directions of movement. The first series represent zones of pressure, the latter, a zone of tension.

(d) Domes and Basins.

The series of domes and basins is the ultimate result of differential movement, and the influence of the two pressures at right angles to each other. The gradual infilling of the basins, especially of the central basin C, is due to a gradually-decreasing rate of movement over the whole area, leading to an increased difficulty of movement over obstructions. Thence a gradient formerly suitable for further movement becomes unsuitable at a later stage, with a consequent stranding of material.

(e) Movement round a spur.

The presence of a neighbouring glacial channel at 80 ft. below O.D., or 120 ft. below the pre-glacial platform readily explains the deflection of the movement from the west by that from the N.N.W. or N.

The channel must have been in existence during the deglaciation of the area, for it is filled with re-arranged boulder clay and glacial sands.

(f) Change of level.

All the disturbed deposits, with the exception of Thanet beds, have been derived from higher levels. The Crag has been brought from 100 ft. or more above O.D. down to at least 30 ft. O.D., and then moved first upwards, and finally in places downwards over the drumloid curves. Its maximum height in the disturbed area is about 60 ft., but the greater part does not reach this level.

4. TOPOGRAPHY.

The hill is a topographical feature entirely of glacial origin, and has points of resemblance to drumlins.

The drainage of the Gipping Valley was by means of the glacial channel, which has not directly influenced deposition of the disturbed area. The deposition of the disturbed deposits has taken place under entirely tranquil conditions.

5. MODERN ICE ACTION AND ITS ANALOGOUS EFFECTS IN THE HADLEIGH ROAD AREA.

The following are the chief points of resemblance between the disturbed deposits and modern glaciers.

1. The presence of the drumloid curves.
2. The frequency of thrust-planes on the exposed limbs of the folds and tip-structure on the leeward limbs.
3. The type of bedding which is entirely dissimilar from water-deposition.
4. The superficial nature of the disturbed deposits.

VII. General Review of the Tectonic Features displayed by Glacial Deposits in East Anglia.

A. PERSISTENT FEATURES OF THE STRUCTURE.

1. Dynamic pressure, and the friction caused by a moving body of ice over local outcrops of comparatively soft material, have disturbed the upper surface of the underlying beds in different ways, according to the plasticity of the material forming the floor of the glacier.

- (a) Chalk has been brecciated and shattered.
- (b) Soft Reading Sands have been moulded into miniature roches-moutonnées.
- (c) Plastic clays have been caused to slide along a horizontal plane until impeded, developing in the process strain-slip cleavage and miniature folds and foliation. London Clay and Thanet Clays are the best media for this type of structure.

2. In all cases of obstruction to movement, the basal disturbed material is ultimately moulded into curves of roche-moutonnée outline, described as the "drumloid curve." This curve is also developed on the surfaces of basal transported masses of material when these become stationary. The basal roche-moutonnée forms the "core" or "nucleus."

3. The "drumloid curve" is composed of two limbs. The iceward side is the limb directly exposed to pressure, and hence is associated with thrust-planes; the protected or leeward side is characterised by flow-structure and the development of tip-heap phenomena. The former has at first a gentle gradient;

the latter, a steeper gradient, and often a graceful development of flow-curves.

4. The succeeding phenomena may be simple or complex according to the effect of several important factors:—

- (a) The lithological composition of the core.
- (b) The amount of material available for the formation of a core.
- (c) The lithological composition of the later deposits, that is, the deposits which subsequently passed over the "cores."
- (d) The decrease in the power of the ice.

In all cases, later material is moulded over the cores, forming a roche-moutonnée over a roche-moutonnée, the upper surface of the core forming a major thrust-plane.

5. Development of the sigmoid curve on the iceward limb of the "cores."

The plastering of material on the iceward limb by means of superimposed "elbow-shaped" minor thrust-planes ultimately builds up a *composite sigmoid curve* which is in the nature of a major thrust plane. This forms a "buttress" to movement, as the "core" has now developed into a minor "horst."

- (a) If the succeeding material is arenaceous, a basin of spoon-shaped outline is formed, or a series of domes and basins.
- (b) If the succeeding material is argillaceous, a curve of anticlinal form is developed.

The curve commences with the formation of a simple anticline. Under suitable conditions this anticline develops into more complicated "folds," including the overfold and diapire. The succession of the types of curves is as follows—anticline, diapire, overfold. The pinching out of the overfold leads to the formation of isolated "slabs" of material which are transported and incorporated in subsequent deposits.

6. The banking of material against the sigmoid curve ultimately leads to the formation of a suitable gradient for further transportation of material.

The upper surface of the contorted deposits becomes a thrust-plane.

7. The increase of pressure shown by the phenomena associated with the sigmoid curve is still further seen in the deposits which overlie the beds (5).

This is shown by the development in the beds of:—

- *1. Overfolds, or "flow-folds."
2. Thrust-planes.
3. Inversion of beds derived from lower geological horizons.

* This "banking" of material on the exposed side of the "cores" may extend for considerable distances, compared with which, the later material deposited on the leeward limb is altogether negligible or, indeed, may be absent.

4. The infilling of the basins.

8. The structure becomes sealed by a deposit of boulder clay.

B. EXTENT OF DISPLACEMENT OF THE DISTURBED DEPOSITS.

The disturbed deposits have moved in two directions, laterally and vertically.

Where the "cores" are composed of transported material, this material has been derived from the immediate outcrop. The material moulded over the cores has been obtained further afield, but from outcrops in the vicinity. This material has usually moved first from higher to lower levels; secondly, during the process of moulding, from lower to somewhat high levels, that is, towards the apex of the asymmetrical curve of the *roche-moutonnée*. Further movement is then downwards.

The juxtaposition of several *roches-moutonnées* may lead to a switchback mode of progression over a limited area.

The greatest distance to which local material has been transported before final deposition is probably less than a mile. This applies to the shelly Crag of the Hadleigh Road Area. The amount of transport of most of the material may reasonably be regarded as much less than this.

On the other hand, the Kimmeridgic Boulder Clay overlying some of the deposits has travelled from the neighbourhood of Ely and contains other material derived from still farther afield.

C. PROBABLE SEQUENCE OF THE MOVEMENTS.

The movements which yielded the structure are exceedingly complex. These are treated in detail for the Hadleigh Road Area. Only a few general principles are summarised here.

Throughout the whole of the genesis of the structures, we are dealing with the forward movement of ice. This movement as shown by the structure was exceedingly slow and gentle. The direction of movement was dominantly in one direction as a whole, but was always modified by obstructions, the tendency being to form curves as shown by the trend of the sigmoid curve when seen in plan.

A horizontal movement became changed to movement along an inclined plane when progress was impeded; movement on the iceward side of the core was aided by the formation of thrust-planes, a general absence of these occurring on the leeward side; hence a complicated series of phases of pressure and tension succeeded one another.

Whilst the movement was always in a forward direction, the stranding of material on the iceward limb of the "core" led to the accumulation of deposits in the reverse direction to the movement of the ice.

Different rates of movement therefore occurred on the two limbs of the "core," the one slow, the other (on the leeward side) quicker.

The stranding of the lower material led to differential movement of the upper beds. The quickest movement therefore occurred on the leeward limb of the asymmetrical curve, as this movement had the additional advantage of being helped by gravity. Hence structure on this limb may be obscured when the deposits are of a sandy nature (such as the Crag), the formation of tensional faults aiding this process.

The rate of movement was in direct proportion to the amount of pressure.

In the case of two directions of pressure, the retarding of movement appears to have been followed by greater tectonic structure and greater deposition of material, as in the case of the Hadleigh Road Area near the Hadleigh Road Bridge.

Movement against the sigmoid curve can be proved to have been nearly vertical, whilst movement towards the close of the infilling of the basins was approximately horizontal.

The absence of structure in the upper boulder clay, which is characteristically widespread, has often been remarked upon by workers in drift deposits.

From observations in Spitsbergen the writer regards this as due to the action of convection-currents in the cellular ice during the downward movement of englacial material towards the lower levels of the glacier. On the other hand, the close packing of the boulder clay in the lower parts has been influenced by pressure.

The deposition of the disturbed material, due to the melting of the interstitial ice, has been exceedingly slow. Even the thinnest strips of boulder clay, London Clay, Crag, etc., have maintained their individuality. There is no confusion or admixture of these one with the other.

The disturbances described in Parts I. and II. of these papers belong to the *roche-moutonnée* type of glacial tectonics. The inversion of the Thanet beds on the iceward limbs, associated with the sigmoid curve, and a squeezed anticline, is the first stage in the commencement of imbricate structure (*Schuppen-Struktur*), wonderfully developed in the analogous glacially disturbed deposits of Lønstrup and the Isle of Møen, Denmark, in the Isle of Rügen, Germany, as well as in other localities.

D. CONCLUSION.

In conclusion, I beg to express my thanks to the Ipswich Borough, and the Great Eastern Railway Engineers, for plans of the ground, and place on record my indebtedness to Profs. E. J. Garwood, F.R.S., and T. C. Chamberlain, and the late G. W. Lamplugh, for their stimulating papers. To my friend,

Prof. P. G. H. Boswell, I am especially grateful for sympathetic interest throughout. To my chief, Prof. W. W. Watts, F.R.S., I am indebted for friendly advice, criticism and facilities for the working out of the results in the Geological Department of the Imperial College of Science.

The publication of this work has been aided by a grant from the Publication Fund of the University of London.

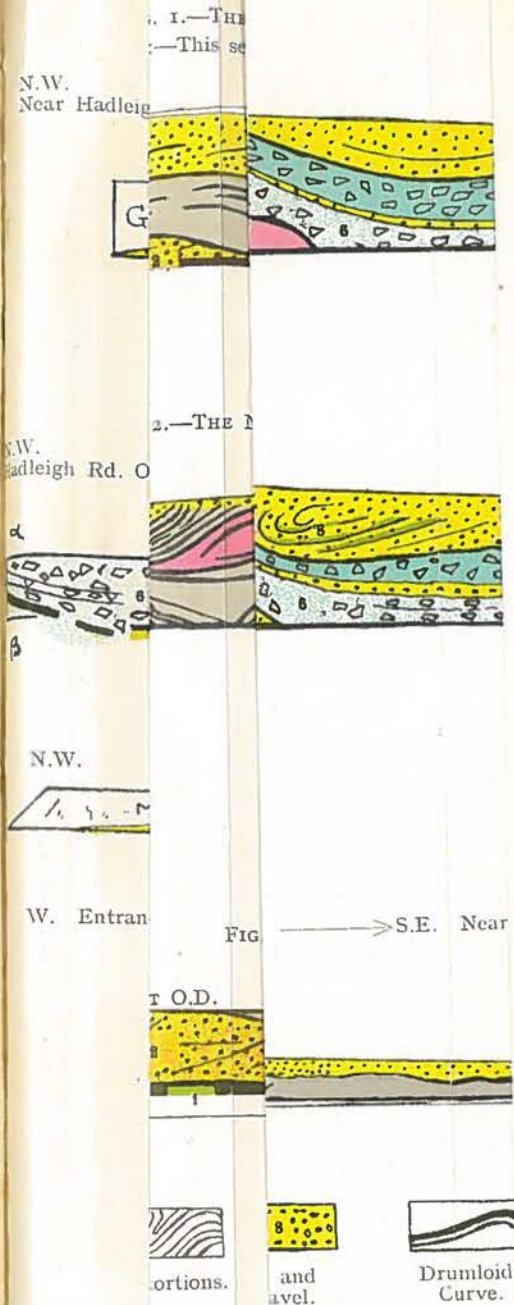


FIG. 1.—THE SOUTH-WESTERN SIDE OF THE RAILWAY-CUTTING, 1911.
 Note:—This section (fig. 1) is reversed to facilitate comparison with fig. 2.

N.W.
 near Hadleigh Rd. Overline Bridge.

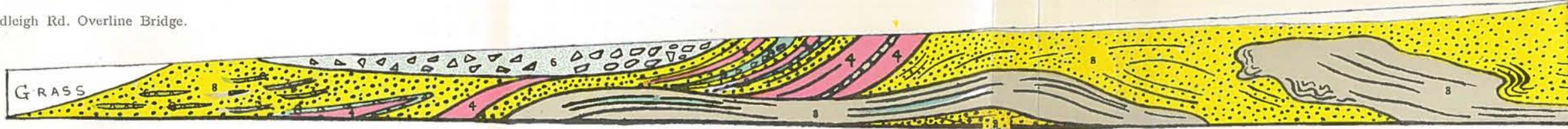
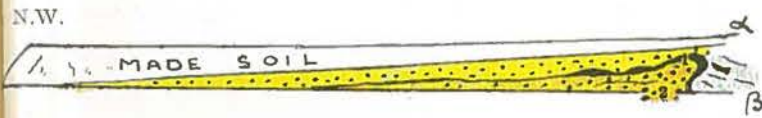
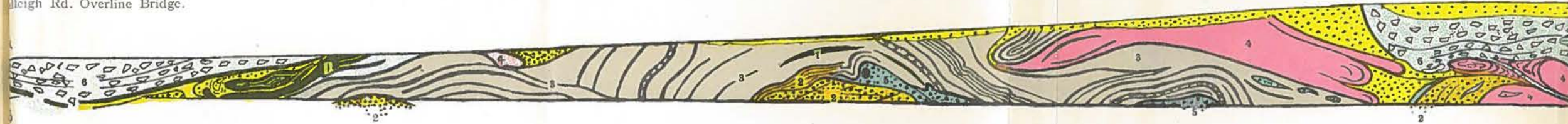


FIG. 2.—THE NORTH-EASTERN SIDE OF THE RAILWAY-CUTTING, 1900 AND 1913

N.W.
 Hadleigh Rd. Overline Bridge.



N.W.
 Entrance to Engineering Works.

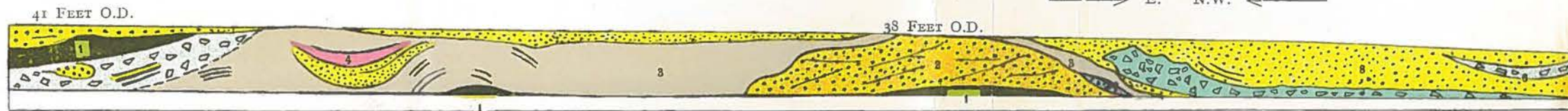
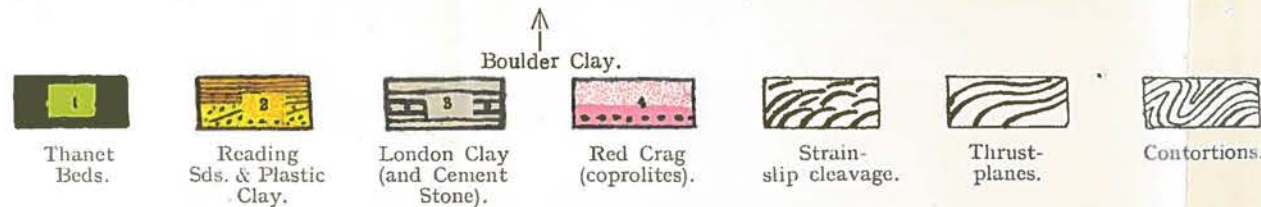


FIG. 3.—THE HADLEIGH ROAD SEWER SECTION, 1913.
 ———> E. N.W. <————



Conventional symbols adopted throughout the paper.

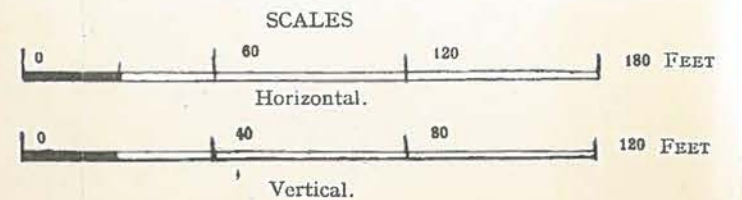


FIG. 1.—THE SOUTH-WESTERN SIDE OF THE RAILWAY-CUTTING, 1911.

Note:—This section (fig. 1) is reversed to facilitate comparison with fig. 2.

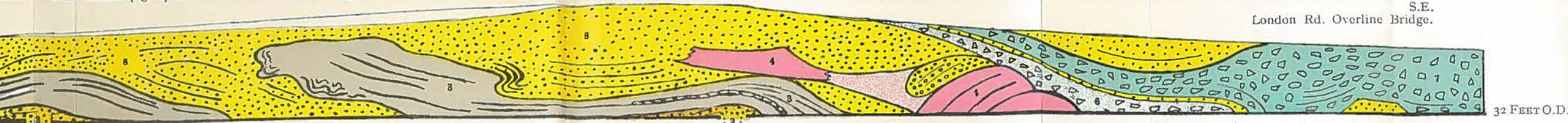


FIG. 2.—THE NORTH-EASTERN SIDE OF THE RAILWAY-CUTTING, 1900 AND 1913

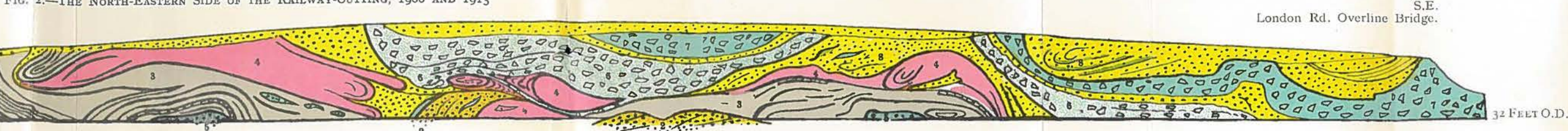
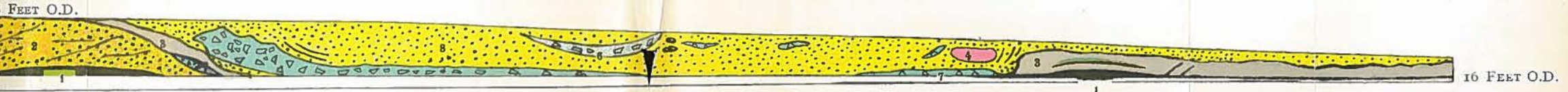


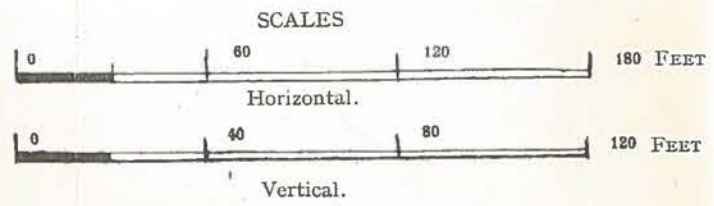
FIG. 3.—THE HADLEIGH ROAD SEWER SECTION, 1913.

→ E. ← N.W.

→ S.E. Near junction of Hadleigh Rd. and London Rd.



Contortions.

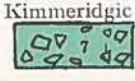


Chalky Gravel.



Bedded

Boulder Clay associated with sand and gravel.



Kimmeridgic



Sd. and Gravel.



Drumloid Curve.



Sigmoid Curve.

