PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Cambering and Valley Bulging in the Gwash Valley at Empingham, Rutland [and Discussion]

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Cambering and valley bulging in the Gwash valley at Empingham, Rutland

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with an appendix by P. R. Vaughan

[Plates 1 and 2]

The construction of a dam at Empingham, Rutland has provided an opportunity to investigate the nature and effect of cambering and valley bulging. A detailed lithostratigraphic sequence has been established and the Upper Lias has been divided into a series of micropalaeontological zones. These features have enabled the internal structure of the Upper Lias to be determined in boreholes and at outcrop. The cambering process results in a progressive valleyward thinning which affects almost the entire Upper Lias sequence. The valley bulges are complex anticlinal structures developed in the valley floors. At depth the steeply inclined strata caught up in the valley bulge gives way along a possible décollement plane to largely undisturbed strata. The valley bulge structures occur throughout the valley and their courses are reminiscent of the trends of the modern valley system. This suggests that they may have been developed in the floors of the ancestral drainage system.

The superficial structures were developed at the time of the Chalky Boulder Clay glaciation. Subsequent development of the valley has been a process of continued downcutting with landslipping and solifluxion being the dominant processes since the last glaciation.

Possible mechanisms for the development of the superficial structures are discussed in the Appendix.

1. Introduction

The basin of the River Gwash lies largely within Rutland, which now forms an administrative division of Leicestershire. The Gwash rises near Nassington and flows eastward, draining the southern part of the Vale of Catmose. An eastward flowing tributary (the north tributary of Chandler (1976)) rises near Oakham and flows across the northern part of the Vale before joining the River Gwash above Empingham [SK 950 086]‡ within the proposed Empingham Reservoir site. The only other tributary is the North Brook, which rises near Cottesmore before flowing east and then south to the confluence with the River Gwash below Empingham. The River Gwash is a tributary of the River Welland which it joins near Stamford.

The catchment of the River Gwash comprises rocks of Lower and Middle Jurassic age. Middle and Upper Lias sediments crop out over the greater part of the basin whilst the Inferior Oolite and Boulder Clay form most of the interfluve ridges.

The Empingham Reservoir will constitute part of a pumped storage scheme. Water abstracted from the Rivers Welland and Nene, during periods of peak flow, will be pumped through 21 km of tunnels and pipelines into the reservoir. The scheme was first examined in 1967 and the detailed site investigation began in 1970. The boreholes, trial pits and the excavations formed

‡ All locations lie within 100 km square SP unless otherwise stated.

during construction provided an opportunity to study the effect of the superficial movements upon the internal structure of the formations affected. It was hoped that this would establish a model which could then be used in analysing the mechanism by which the movements may have occurred. Mr P. Horswill is employed as an engineering geologist by Messrs T. & C. Hawksley, the Consulting Engineers to the Welland and Nene River Division, while Mr A. Horton examined many of the boreholes and exposures in the Upper Lias on behalf of the Institute of Geological Sciences.

2. Topography

The proposed reservoir will have a Y shape since the valleys of the River Gwash and its main tributary above Empingham will be flooded. In the vicinity of the dam the floodplain lies at about 53 m O.D. while the highest point on the interfluve ridges is about 110 m O.D. The base of the Boulder Clay lies between 98 and 105 m O.D. (figure 1).

The angles of the vally slopes in the reservoir area are generally less than 5°. These low-angle slopes are developed on hard and soft rock formations alike though very local increases in slope angle may be associated with the change in lithology at formational boundaries.

3. Geological sequence

(a) *Middle Lias*

The oldest rocks cropping out in the catchment of the River Gwash are the Middle Lias Silts and Clays which occur as inliers in the valley floors in the western parts of the basin. This division comprises medium to dark grey micaceous silts and silty mudstones with up to 0.2 m thick calcareous siltstones and silty limestone beds.

The overlying Marlstone Rock Bed gives rise to extensive bench features southeast of Oakham. It consists of up to 2.5 m of pale greenish grey chamositic oolitic shelly shell-fragmental limestone with some thinner bands of sideritic or chamositic fine-grained limestone. When unweathered it is very hard and massive with few widely spaced joints, but at outcrop it is oxidized and decalcified in parts to a flaggy to rubbly bedded ironstone with secondary iron oxide veins.

(b) *Upper Lias*

The Upper Lias is a predominantly argillaceous formation which in the reservoir area varies in thickness from 54.7 m to about 37 m. The greater part of this variation results from thinning as the result of cambering (p. 432). The original maximum thickness may have been as much as 62 m. The Upper Lias is overlain disconformably by the Northampton Sand and pre-Bajocian (pre-Inferior Oolite) erosion may have resulted in some very slight regional thinning across the reservoir site. The Upper Lias can be divided into three main units (Horton, Shephard-Thorn & Thurrell 1974, p. 8): the Fish Beds Member at the base, the Cephalopod Limestones Member and the bulk of the formation which consists largely of mudstones and has not been given a separate name (figure 2). Individual marker horizons; the Pisolite Bed, the 'Smartie' Nodule Band and the Ammonite Nodule Bed have been recognized locally (Horton & Coleman, in press).

The Fish Beds Member (1.25–1.59 m) rests directly upon the Marlstone and comprises greenish grey to pale olive and brown finely laminated shales and calcareous mudstones which may pass laterally into nodular limestones. The shales and mudstones are moderately hard and massive when fresh but weather at outcrop to pale buff to brown very firm clay.

The Cephalopod Limestones Member (about 8–10 m) comprises calcareous mudstones and

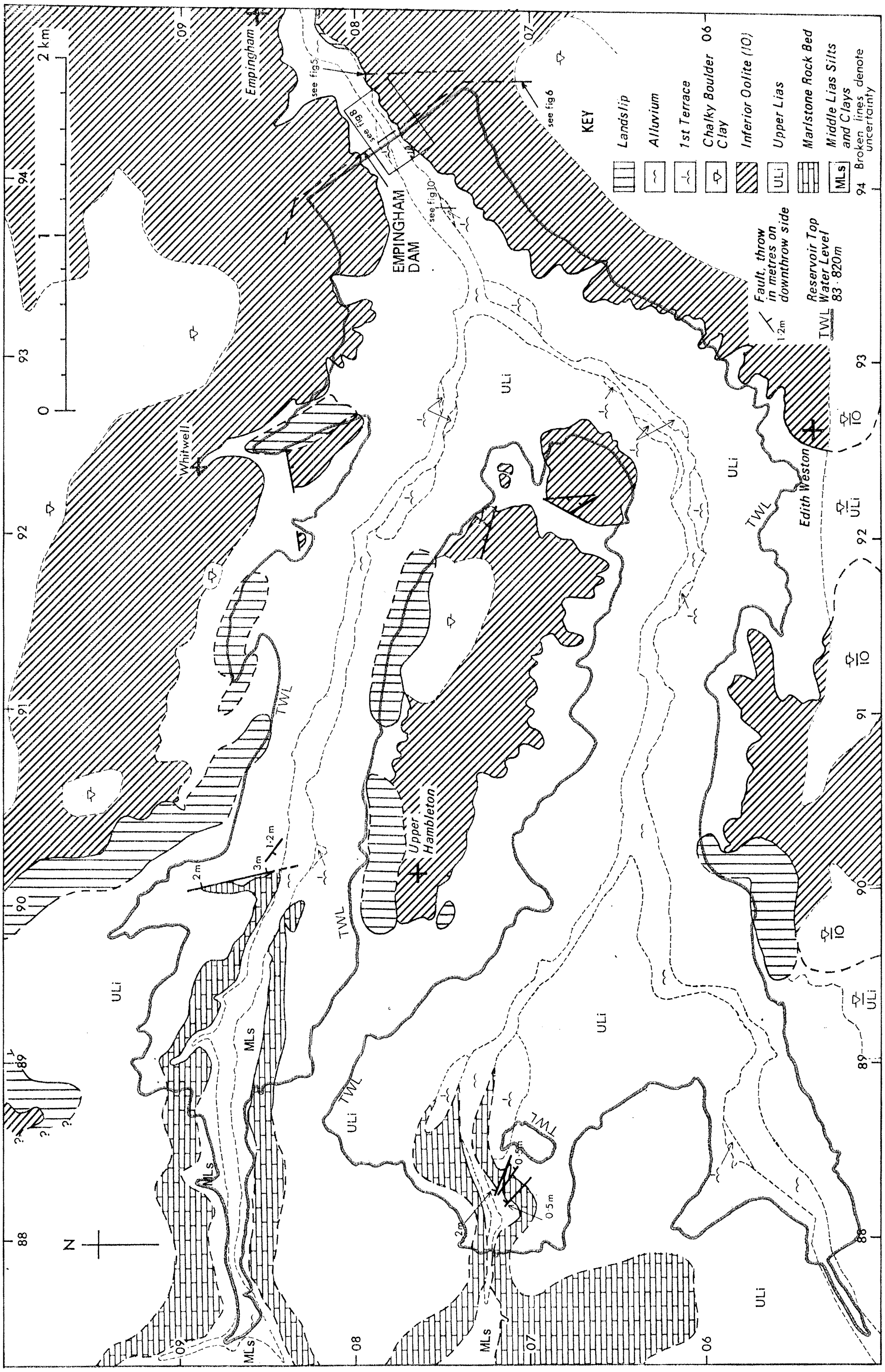

Figure 1. Geological sketch map of the Empingham Reservoir site.

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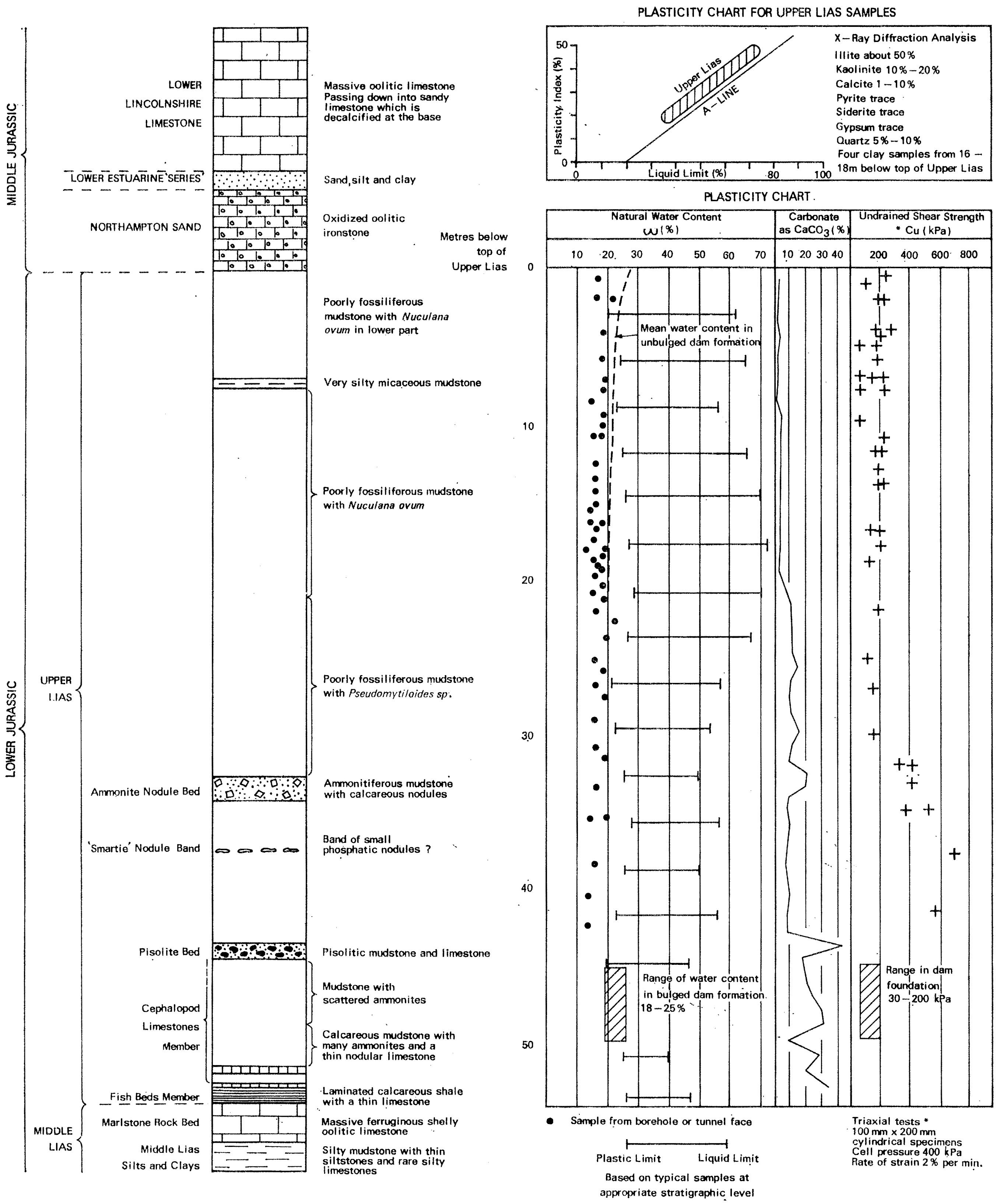


FIGURE 2. Generalized geological sequence based on borehole SD6 and corresponding engineering properties of the Upper Lias (Moisture content based on samples of known stratigraphic level in boreholes and tunnels. Plasticity determined from borehole SD6 samples. Carbonate content based on sequence in borehole B14 and strengths from boreholes along tunnels and at dam site.)

marl with thin pale to medium grey rather nodular fine-grained micritic limestones. The mudstones are generally blocky but some thin fissile horizons are present. Fossils are present throughout and distinct bands with very coarse '*Chondrites*' type mottling produce marker horizons which can be traced in deeper excavations.

The base of the Pisolite Bed has been taken as the top of the Cephalopod Limestones Member. The Pisolite Bed (0.8–1.7 m) is a medium-grey massive calcareous mudstone with pale grey to olive-grey micritic slightly ferruginous limestone masses and scattered phosphatic pisoliths.

The overlying beds are medium grey slightly fissile to blocky mudstones. They appear relatively uniform in hand specimen but become slightly more silty upward. The 'Smartie' Nodule Band occurs about 5.0–5.5 m above the Pisolite Bed. Its characteristic discoidal phosphatic nodules can be recognized in boreholes and traced in deep excavations. A more important marker horizon is the Ammonite Nodule Bed which occurs some 8.5–10 m above the Pisolite Bed. It comprises very hard ammonitiferous limestone nodules set in a calcareous mudstone matrix. Calcareous and possibly sideritic nodules are present throughout the overlying mudstones and are sufficiently abundant at some levels to form beds traceable over short distances in excavations. The uppermost strata of the Upper Lias are silty and micaceous mudstones and at least one bed of very silty micaceous mudstone is present in the topmost 8 m.

(*c*) *Inferior Oolite*

The Northampton Sand rests abruptly upon the Upper Lias mudstones. Generally it ranges up to 5.6 m in thickness, but 6.2 m was recorded in borehole SD7† [9469 0682]. It consists of greenish grey chamositic oolith and shell debris limestones with less ferruginous bands. Throughout the environs of the reservoir site it has been oxidized and leached to ironstone with the development of cavernous structures, secondary ironstone veins and box-ironstone structures. It is rubbly weathering and rather soft, much broken and shattered.

The Lower Estuarine 'Series' (up to 2.6 m thick) comprises a variable sequence of lilac-tinted to pale grey sands with clayey beds and brownish grey silts and silty clay, some with sheared-seatearth lithology.

The Lower Lincolnshire Limestone is at least 9 m thick and consists of massively bedded pale cream to buff oolitic shell-fragmental limestones with beds of finer grained sandy limestone at the base. Locally the upper beds are completely weathered to flaggy and rubbly limestones while decalcification of the basal beds give rise to pale fawn sands similar in texture to those in the underlying Lower Estuarine 'Series'.

4. Palaeontology of the Upper Lias

Fossils occur throughout the formation and three groups have been found to be of value in determining horizons within the Upper Lias. Ammonites are common near the base of the formation, particularly in the Cephalopod Limestones Member, and a zonal sequence can be established. The upper part of the formation, which lacks persistent marker horizons, is poorly fossiliferous and diagnostic ammonites are rare and the subzones are relatively thick. Hence the ammonite zones and subzones caould not be used to examine thickness changes within the Upper Lias.

† SD7 was one of the pre-construction site investigation boreholes at the Empingham dam-site. All other boreholes with alphabetical prefixes are related to the reservoir project.

Microfossils occur throughout the formation and have the advantage over ammonites that any sample of unweathered mudstone can be broken down to yield a fauna. Two groups, the foraminiferida and the ostracoda, were used to establish a series of assemblage zones within the Upper Lias which can be traced throughout the Empingham Dam site. Five foraminiferal assemblage zones have been recognized and the thickness of these zones in boreholes along the main axis of the dam has been determined (Horton & Coleman, in press). The ostracoda can be used to establish three assemblage zones whose boundaries coincide with those of the foraminiferal divisions (Bate & Coleman 1975).

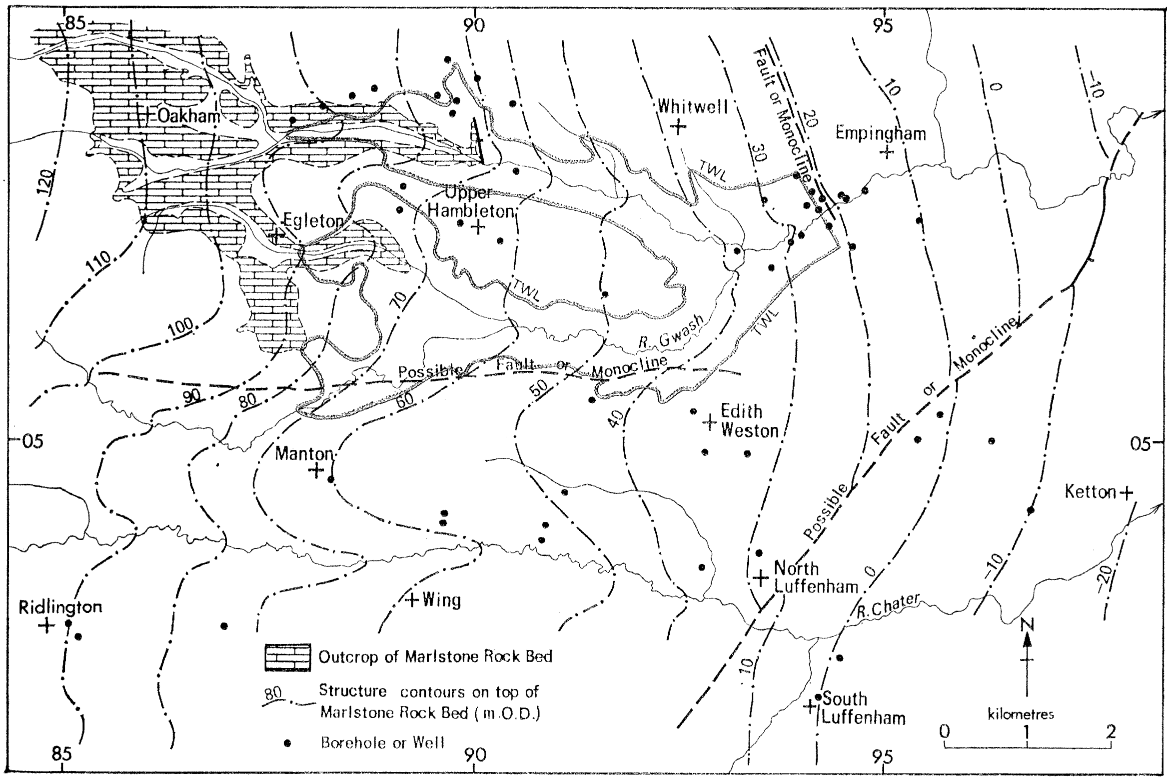


FIGURE 3. Contours on the top of the Marlstone Rock Bed in the vicinity of the Empingham Reservoir site.

5. CAMBERING

(a) General characters

The Empingham Reservoir Site lies within the Northampton Sand Ironstone Field (Hollingworth & Taylor 1951) the resurvey of which during the Second World War led to the recognition of the widespread development of superficial structures (Hollingworth, Taylor & Kellaway 1944). Cambered Inferior Oolite strata drape the higher ground and their base falls progressively towards the valleys. Thus locally the overall dip of the cambered strata is towards the lower ground and in the case of isolated hills this may give rise to quaquaversal dips.

At Empingham, the regional dip of the Inferior Oolite and the underlying Upper Lias is about 1 in 100 ($\frac{1}{2}°$) to the ENE.† This was determined from structure contours drawn on the

† All bearings are related to Grid north.

top of the Marlstone Rock Bed (figure 3) and from the relative levels of the base of the Inferior Oolite in the interfluve areas, where it is unaffected by cambering. In contrast, contours on the base of the Northampton Sand Ironstone at the dam site (figure 4) show an approximately southwest to northeast trend, but superimposed on this is a weak convergence towards the valley axis. These generalized contours are based on information from boreholes, excavations and the surface outcrop of formational boundaries. They show average valleyward dips of 1 in 30 (2.0°) on the north side of the valley and 1 in 25 (2.3°) on the south side.

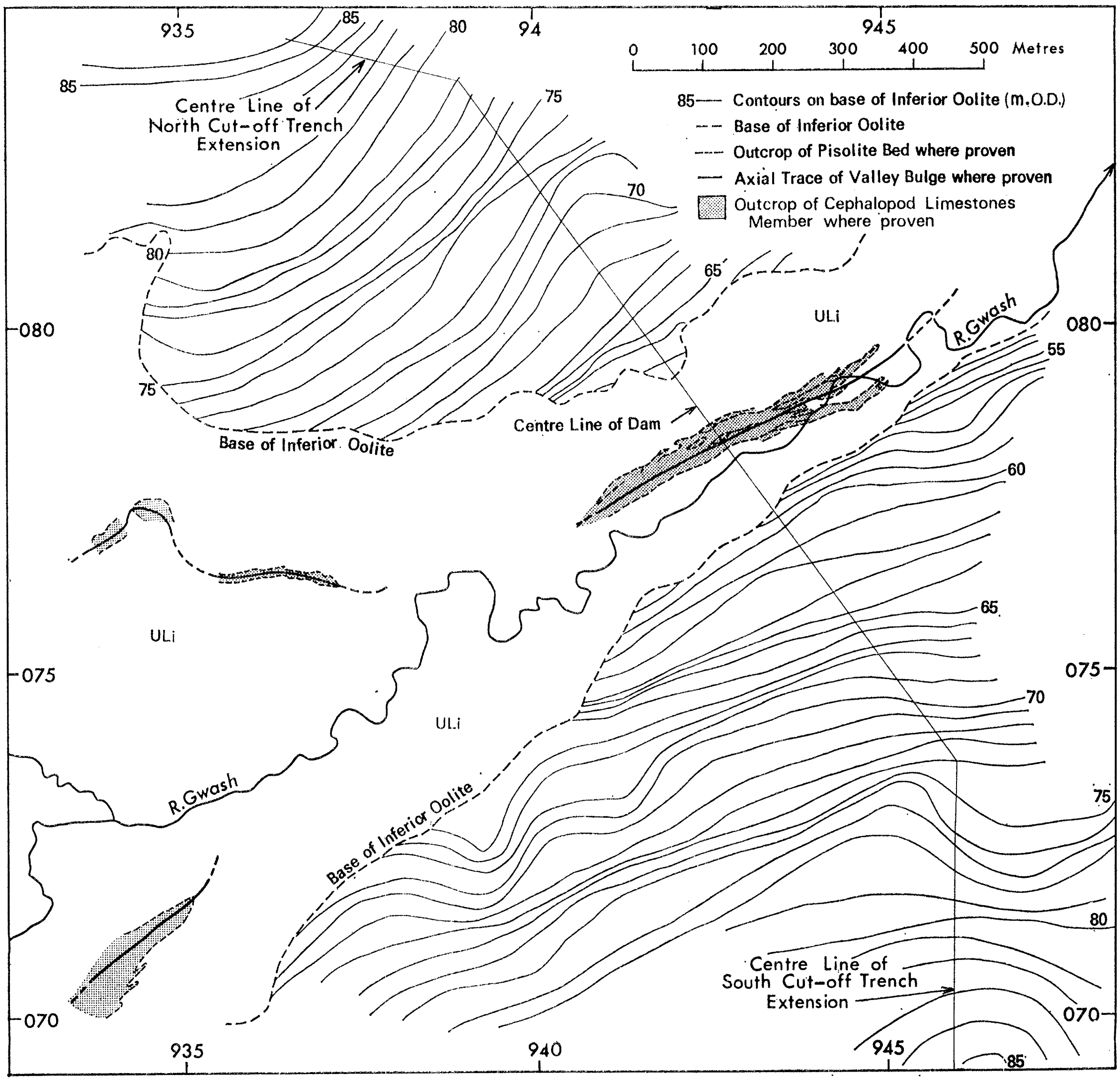


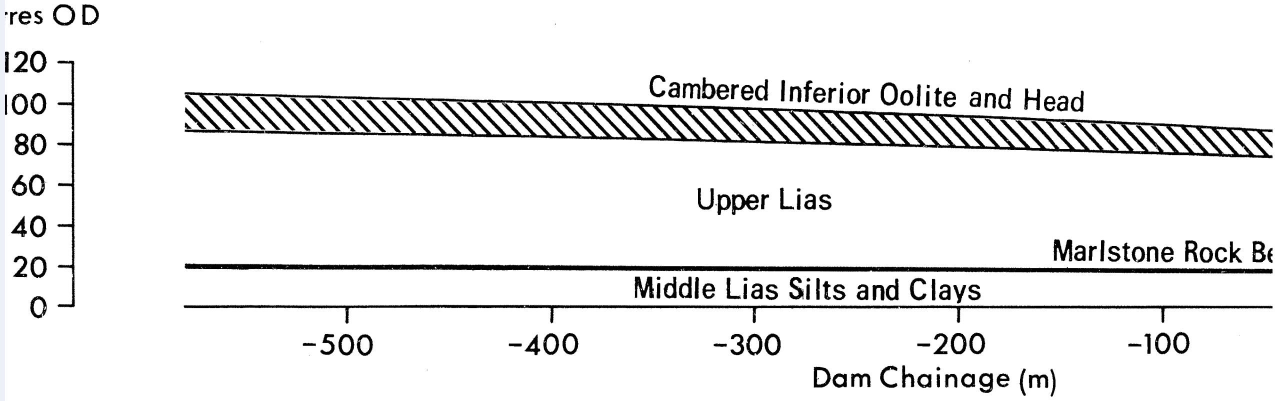
FIGURE 4. Generalized contours on the base of the Inferior Oolite at the Empingham Dam site to illustrate the effect of cambering.

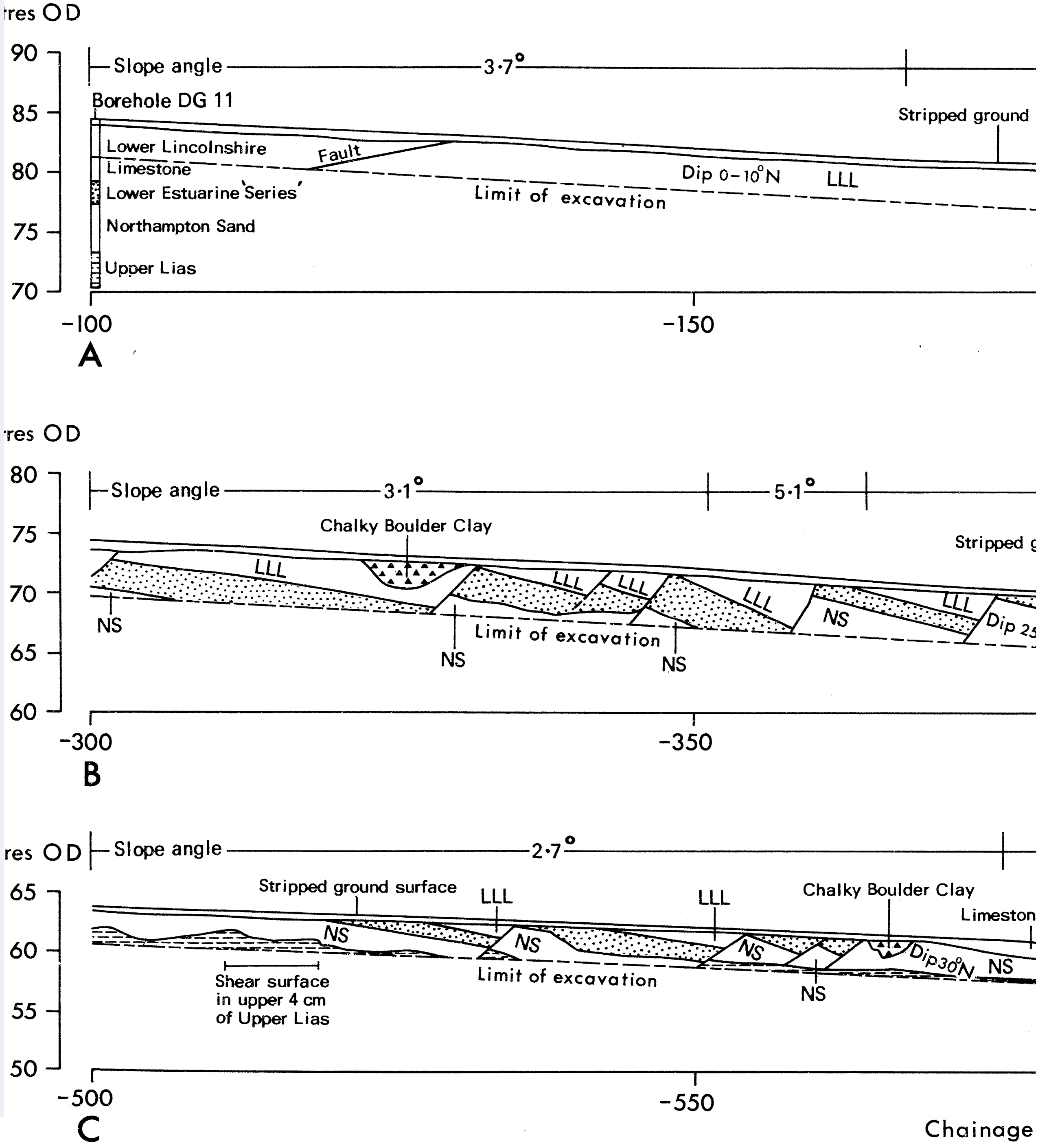
Excavations through the Inferior Oolite have shown that this contoured plan (figure 4) greatly simplifies the actual structure of the camber sheets. The latter consist essentially of a series of competent blocks of strata in which the beds dip valleywards at angles of up to 30°. The blocks are separated by normal faults, generally dipping between 45 and 60° towards the interfluves and with throws of between 1 and 4 m. The net effect of this 'dip-and-fault' structure with steepened dips towards the valley in the camber blocks and the upthrows on the valleyward side of the intervening faults is an overall lowering of the Inferior Oolite towards the valley floor. On the south side of the valley, this lowering is between 23 and 26 m vertically over a horizontal distance of about 800 m. Detailed records along a 4 m deep pipe-line trench, which runs obliquely across the south side of the valley at about 20° to the line of steepest slope, showed that in that area the faults had a mean separation of about 15 m (figure 5). Excavations for the broad foundation of the dam have exposed the weathered basal portions of several camber blocks and shown that the faults persist laterally for at least 30 m (figure 7). The faults are readily recognizable in the Northampton Sand ironstone and in the thinly bedded Lower Estuarine 'Series' sands and clays. In the latter the fault trace is often sharply defined and may be only a few centimetres wide, often containing powdery calcite. Only rarely could the faults be traced into the Upper Lias mudstones. In one instance, however, on the north side of the valley, a fault with a throw of 0.26 m at the base of the Northampton Sand passed downwards into a single polished shear surface in the Upper Lias. This shear surface could be traced some 15 m laterally across the floor of the dam cut-off trench and also through a 1.5 m deep inspection trench. The fault could thus be shown to penetrate at least 2 m into the Upper Lias.

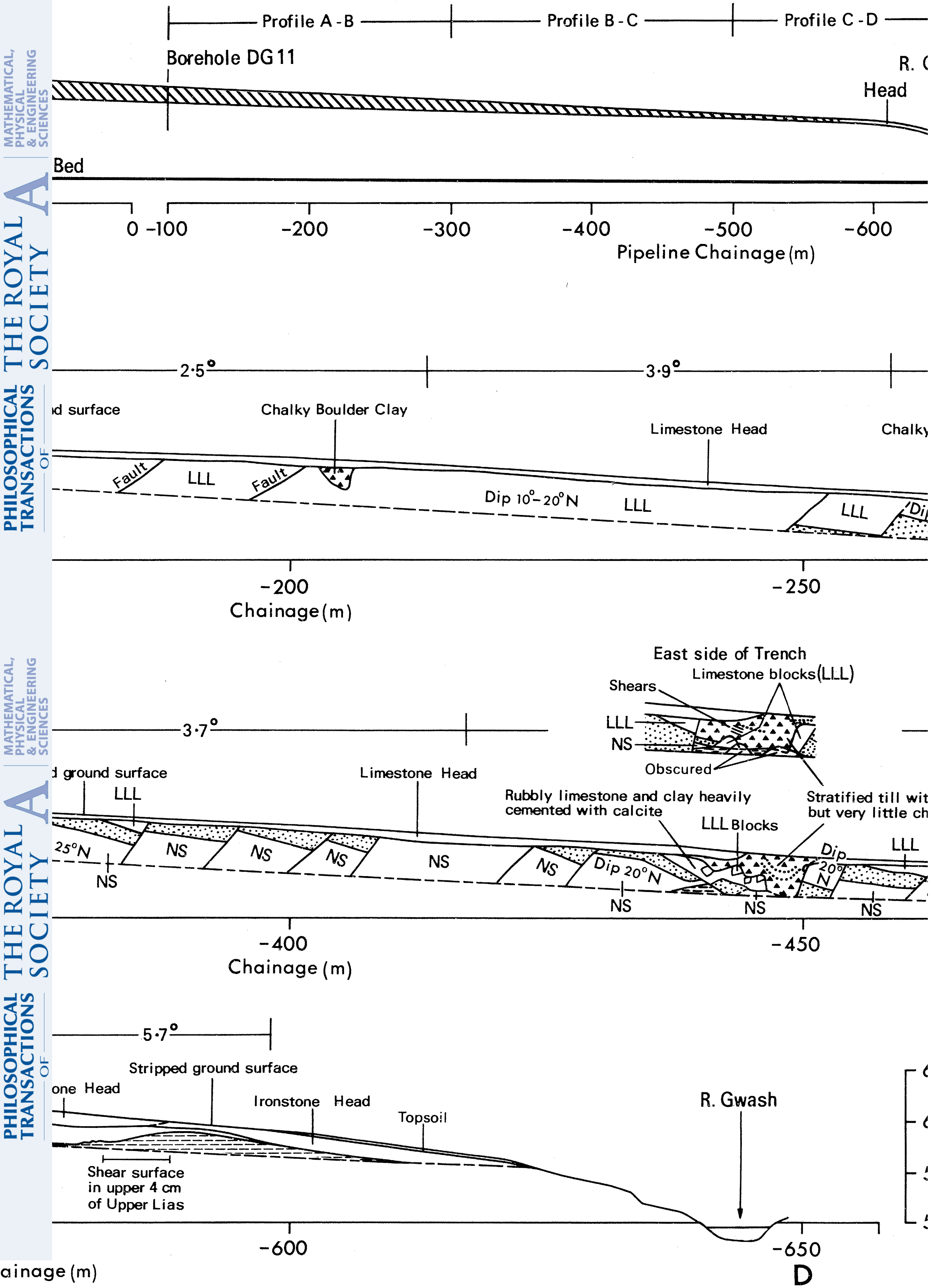
The large-scale fracturing which occurs during the cambering process may also lead to the development of 'gulls'. These may be voids or when larger become infilled with the overlying strata. At Empingham, the 'gulls' all contain Chalky Boulder Clay and are up to 4 m deep. For the most part they appear to be closely associated with the camber faults and may themselves be the infilled upper parts of fault structures. However, in the case of the 'gull' 12 m wide at Chainage – 450 m in the pipe trench (figure 5), an open rift appears to have been formed by downslope movement of the camber blocks on the footwall side of the pre-existing normal fault before the deposition of the Chalky Boulder Clay. The subsequent collapse of both hanging- and foot-walls partly filled the 'gull' with limestone rubble before the Chalky Boulder Clay occupied the remaining void (figure 11). The movement of the camber blocks appears to have been accompanied by both shearing and small-scale folding of the Upper Lias.

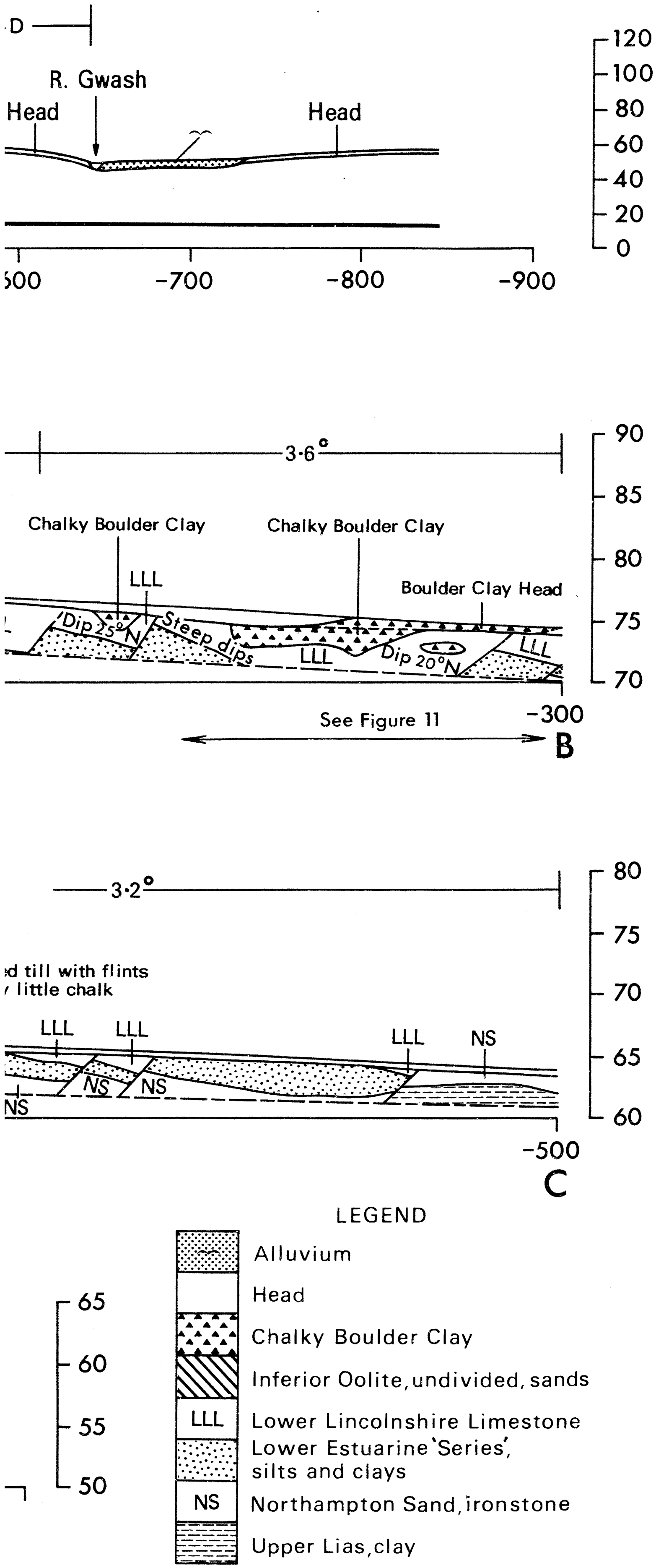
Thinning of the Inferior Oolite formations appears to have occurred during cambering. In the interfluve area to the south of the dam site the Northampton Sand is up to 5.2 m thick but this decreases gradually to about 3.5 m at the edge of the proposed reservoir. Thinning of the Lower Estuarine 'Series' is also apparent and the presence of very small scale normal faulting in this formation within the major fault-controlled blocks suggests that this may be the cause. Similar faulting was not recorded in the Northampton Sand but may be present. Open joints with widths up to 0.05 m occur in the Northampton Sand, which weathers to irregular block-like masses. As cambering develops the formation becomes increasingly broken and it is probable that the tension created during this process would cause movements between joint-controlled masses comparable to normal faulting. As the degree of weathering increases it would give rise to fine-grained and soluble weathering products, these would be removed by the groundwater and thus possibly contribute to the thinning process. The groundwater issues as springs at the base of the cambered strata on the valley sides at the present day. In excavations, groundwater flows were concentrated at the base of the Northampton Sand, but individual springs rarely exceeded 1 l/s. Above the water table, which lies very close to the top of the Upper Lias, calcite

FIGURE 5. Development of dip and fault structures in the Inferior Oolite exposed in a pipeline trench at the Empingham Dam site.


res OD
120
100
80
60
40
20
0
Cambered Inferior Oolite and Head
Upper Lias
Marlstone Rock Be
Middle Lias Silts and Clays
-500
-400
-300
-200
-100
Dam Chainage (m)


res OD
90
85
80
75
70
Slope angle 3·7°
Borehole DG 11
Stripped ground
Lower Lincolnshire
Limestone
Fault
Lower Estuarine Series
Northampton Sand
Upper Lias
Dip 0–10° N
LLL
Limit of excavation
-100
-150
A
res OD
80
75
70
65
60
Slope angle 3·1°
5·1°
Chalky Boulder Clay
Stripped g
LLL
NS
Limit of excavation
Dip 25
-300
-350
B
res OD
Slope angle 2·7°
65
60
55
50
Stripped ground surface
LLL
Chalky Boulder Clay
Limeston
NS
Dip 30° N
Shear surface
in upper 4 cm
of Upper Lias
Limit of excavation
-500
-550
C
Chainage


Profile A - B
Profile B - C
Profile C - D
Borehole DG 11
R. G
Head
Bed
0 -100
-200
-300
-400
-500
-600
Pipeline Chainage (m)
2·5°
3·9°
d surface
Chalky Boulder Clay
Limestone Head
Chalky
Fault
LLL
Fault
Dip 10°–20°N
LLL
LLL
Di
-200
Chainage (m)
-250
East side of Trench
Limestone blocks (LLL)
Shears
LLL
NS
Obscured
3·7°
d ground surface
LLL
Limestone Head
Rubbly limestone and clay heavily
cemented with calcite
Stratified till wit
but very little ch
LLL Blocks
25°N
NS
NS
NS
NS
NS
NS
Dip 20°N
Dip 20° N
LLL
NS
NS
NS
-400
Chainage (m)
-450
5·7°
Stripped ground surface
one Head
Ironstone Head
Topsoil
R. Gwash
Shear surface
in upper 4 cm
of Upper Lias
-600
-650
ainage (m)
D



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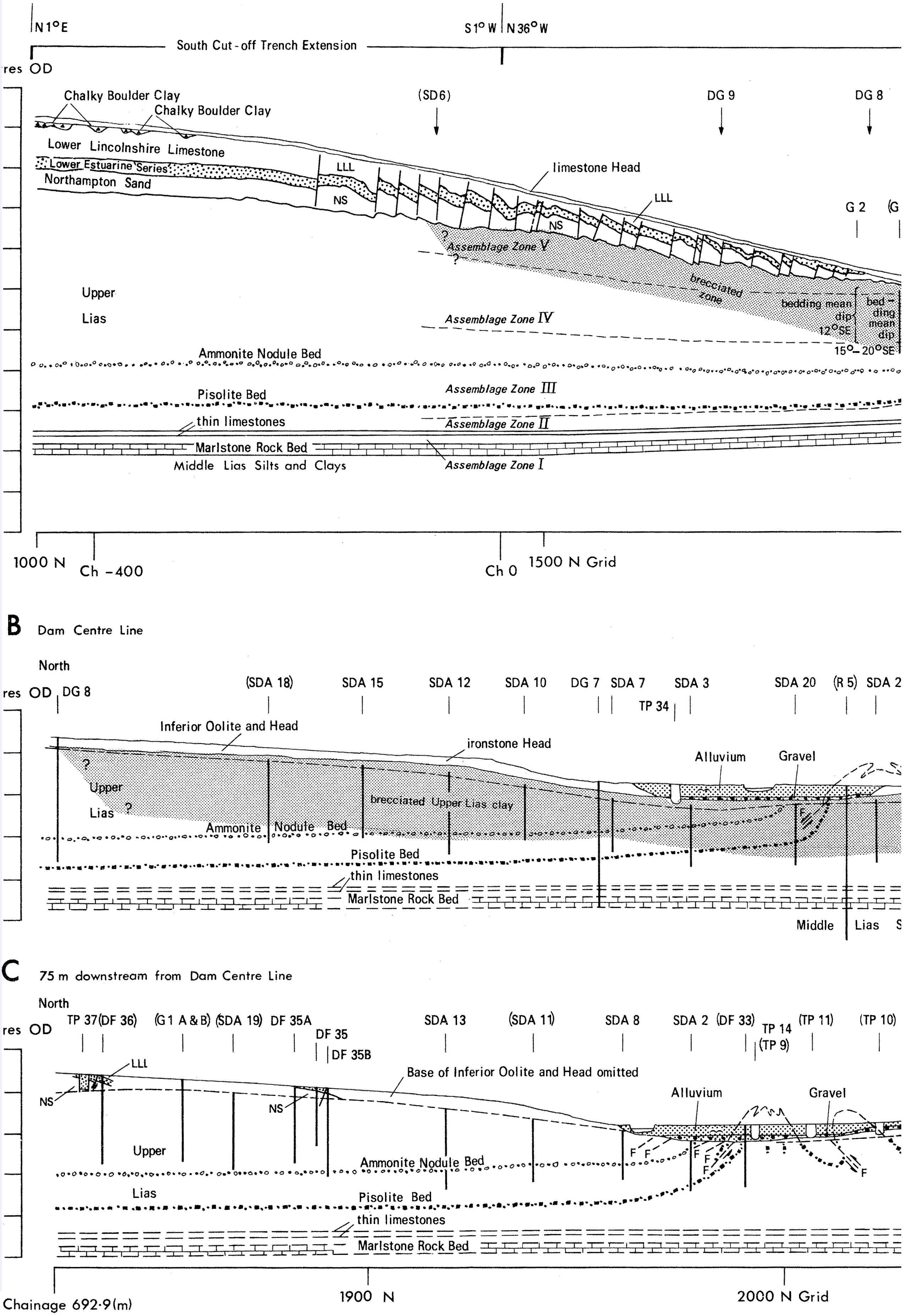
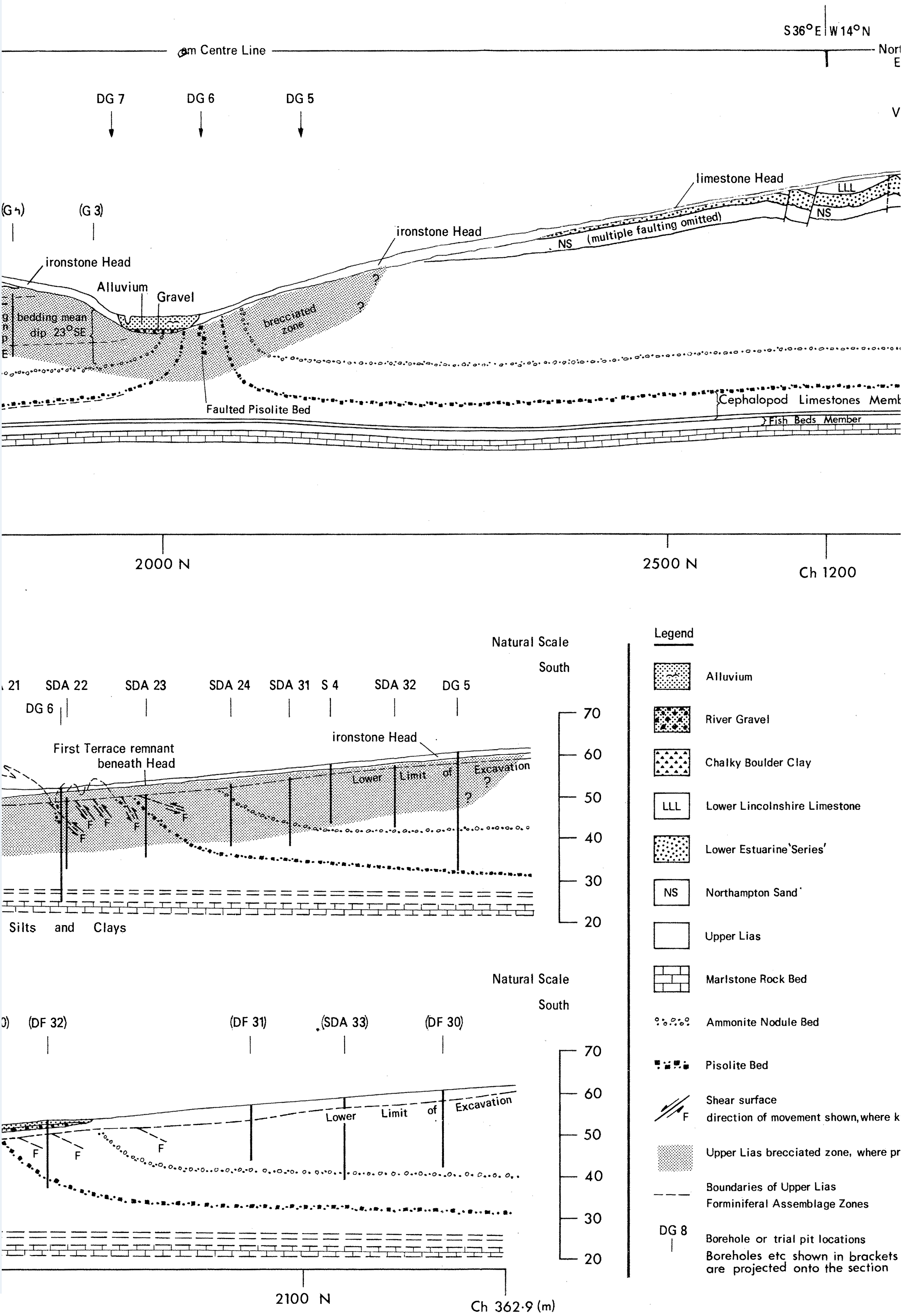
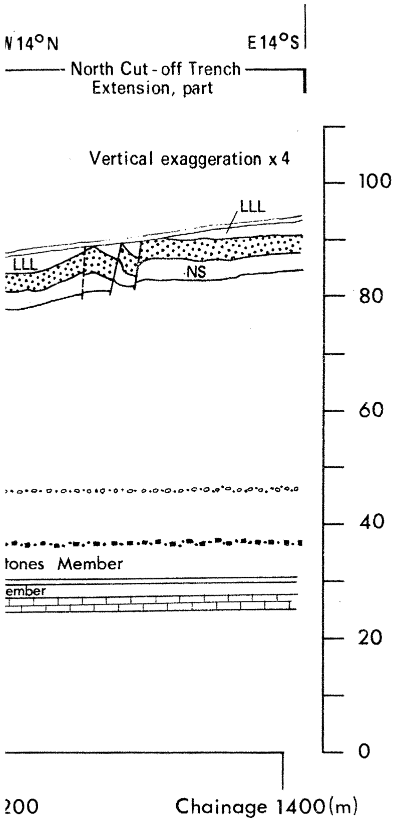


N 1° E
S 1° W
N 36° W
South Cut-off Trench Extension
res OD
Chalky Boulder Clay
Chalky Boulder Clay
Lower Lincolnshire Limestone
Lower Estuarine Series
Northampton Sand
(SD6)
DG 9
DG 8
LLL
NS
limestone Head
LLL
NS
G 2
Assemblage Zone V
brecciated zone
bedding mean dip 12°SE
bedding mean dip 15°–20°SE
Upper
Lias
Assemblage Zone IV
Ammonite Nodule Bed
Pisolite Bed
Assemblage Zone III
thin limestones
Assemblage Zone II
Marlstone Rock Bed
Middle Lias Silts and Clays
Assemblage Zone I
1000 N
Ch −400
Ch 0
1500 N Grid
B
Dam Centre Line
North
res OD
DG 8
(SDA 18)
SDA 15
SDA 12
SDA 10
DG 7
SDA 7
SDA 3
TP 34
SDA 20
(R 5)
SDA 2
Inferior Oolite and Head
ironstone Head
Alluvium
Gravel
Upper
Lias
brecciated Upper Lias clay
Ammonite Nodule Bed
Pisolite Bed
thin limestones
Marlstone Rock Bed
Middle Lias
C
75 m downstream from Dam Centre Line
North
res OD
TP 37
(DF 36)
(G1 A & B)
(SDA 19)
DF 35A
DF 35
DF 35B
SDA 13
(SDA 11)
SDA 8
SDA 2
(DF 33)
TP 14
(TP 9)
(TP 11)
(TP 10)
LLL
NS
NS
Base of Inferior Oolite and Head omitted
Alluvium
Gravel
Upper
Lias
Ammonite Nodule Bed
Pisolite Bed
thin limestones
Marlstone Rock Bed
F
Chainage 692·9(m)
1900 N
2000 N Grid


S 36° E
W 14° N
℄m Centre Line
Nort
E
V
DG 7
DG 6
DG 5
(G 4)
(G 3)
ironstone Head
Alluvium
Gravel
bedding mean dip 23° SE
brecciated zone
ironstone Head
limestone Head
LLL
NS
(multiple faulting omitted)
Faulted Pisolite Bed
Cephalopod Limestones Memb
Fish Beds Member
2000 N
2500 N
Ch 1200
Natural Scale
South
21
SDA 22
SDA 23
SDA 24
SDA 31
S 4
SDA 32
DG 5
DG 6
First Terrace remnant beneath Head
ironstone Head
Lower Limit of Excavation
F
Silts and Clays
70
60
50
40
30
20
Natural Scale
South
(DF 32)
(DF 31)
(SDA 33)
(DF 30)
Lower Limit of Excavation
F
70
60
50
40
30
20
2100 N
Ch 362·9 (m)
Legend
Alluvium
River Gravel
Chalky Boulder Clay
LLL
Lower Lincolnshire Limestone
Lower Estuarine 'Series'
NS
Northampton Sand
Upper Lias
Marlstone Rock Bed
Ammonite Nodule Bed
Pisolite Bed
Shear surface
direction of movement shown, where k
Upper Lias brecciated zone, where pr
Boundaries of Upper Lias Forminiferal Assemblage Zones
DG 8
Borehole or trial pit locations
Boreholes etc shown in brackets are projected onto the section



stone

hown, where known

one, where proven

s

Zones

ations

in brackets
e section

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had been deposited on joint surfaces and occasionally completely filled them. However, no calcite bands of the type recorded by Hollingworth and his co-workers (1944) have been seen at Empingham.

The Upper Lias at Empingham shows a reduction in thickness from about 55 m in Borehole SD6 [9472 0737], south of the dam site, to about 44 m at Borehole DG9 [9447 0756] about midway down the south side of the valley (figure 7). Comparison of the structure contours at the base of the Inferior Oolite and the top of the Marlstone Rock Bed in the interfluve area south of the dam site suggests that in this area the thickness of the Upper Lias approaches 62 m. Hereabouts the overlying strata appear to be unaffected by superficial structures other than small gulls so that this may be the true 'un-cambered' thickness of the formation at Empingham. This may be compared with the 60.6 m of Upper Lias proved in a deep borehole (B14) at Wothorpe [TL 0328 0518], near Stamford, in the plateau area of the Easton–Nassington faulted mass and 63 m at Ridlington [8521 0270] about 10 km to the southwest.

The micropalaeontological zonation of the Upper Lias enabled the nature of the progressive valleyward thinning of the formation to be determined. It was found (Horton & Coleman, in press) that in the cambered area all the foraminiferidal assemblage zones were reduced in thickness (table 1).

Table 1. Thickness variation within the Upper Lias Foraminiferal Assemblage Zones of the River Gwash valley

Foraminiferal Assemblage Zone	borehole no. and estimated zonal thickness/m		
	SD6	DG9	DG7
V	5.90–6.90	7.05–7.30	absent due to erosion
IV	18.20–21.00	12.50–12.75	> 6.25
III	21.00–24.80	17.25–17.50	13.00–13.25
II	4.00–6.00	5.25–6.00	8.25–8.50
I	0.90–1.90	1.20–1.40	0.91–1.16
total	54.80	44.00	> 26.00

The greater part of the thinning appears to have taken place in Assemblage Zones III and IV, which form the bulk of the Upper Lias Clay, although disturbance of the upper part of the formation by 'dip-and-fault' movement in the Inferior Oolite and underlying Lias may have partly obscured a similar valleyward thinning in Assemblage Zone V. The thinning is seen to continue at least as far as borehole DG7 [9431 0778] where Assemblage Zone V is absent. This borehole also shows a significant increase in the thickness of Assemblage Zone II, indicating a change in the pattern of deformation as the bulge structure in the valley floor is approached.

As part of the dam-site investigation, three pairs of boreholes (G1A and G1B, G2A and G2B, and G3A and G3B) were put down on the south side of the valley to depths of up to 19.3 m in the positions shown on figure 6*a*. Borehole pair G2 lies in the plane of the section just south of DG8 while borehole pairs G1 and G3 have been projected upstream 95 and 165 m respectively from their plan positions shown in figure 8. The boreholes in each pair were 1 m apart. Con-

Figure 6. Horizontal sections across the Gwash valley showing the nature of the cambering and valley bulging.

tinuous open drive tube samples were taken from each borehole. The samples were orientated so that both the dip and the strike of any planar structural features, such as bedding, jointing and fissuring, could be determined. The results of the structural analysis (Walbancke 1972, unpublished report) indicated a mean bedding strike of N 44° E (i.e. approximately parallel to the valley axis at this point) but a mean bedding dip of 17° to the southeast. The mean dip in each pair of boreholes varied from 12° SE in G2, the furthest up the valley side, through 15–20° SE in G1 to 23° SE in G3 close to the valley floor. These observations are clearly at variance with the known regional trend of the bedding and also with the apparent gentle dips of the marker beds and the assemblage zone boundaries determined from their known positions in the boreholes. The implications of these observations in relation to cambering and valley bulging is discussed later. A further structural complication is apparent in the downstream pairs G1 and G3. Bedding strikes in the direction N 30° W with dips 15–20° E were noted in G3 and these may be related to the possible monoclinal fold or fault which is present in the Marlstone Rock Bed at the dam site downstream of the centre line (figure 3). In G1, both major and minor structural trends were less well marked and it seems that this pair of boreholes may lie close to the axis of the monocline or to have passed through a fault zone associated with the monocline.

(b) *Brecciation of the Upper Lias*

The fabric of the Upper Lias in the greater part of all the boreholes at the dam site was disturbed giving the material a brecciated texture. Lithorelics of mudstone (clay) with bedding traces were found to be embedded in a matrix of slightly softer remoulded clay in which the bedding was no longer visible. During the logging of the G1, G2 and G3 boreholes, the relative proportions of lithorelics greater than 10 mm across and matrix material were assessed visually and a semi-quantitative grade given to each section of the samples examined. Four grades of material were distinguished separated arbitrarily on the basis of the proportion of remoulded matrix being greater than 75 %, between 50 and 75 %, between 25 and 50 % or less than 25 %. Overall, the proportion of remoulded matrix material in these boreholes decreased with depth but was still found to form between 50 and 25 % of the samples at a depth of 19 m below ground level. Rotation of the lithorelics was apparent in some of the samples, but this was usually only significant in the shallower sections of the boreholes and consequently did not interfere greatly with the assessment of bedding dip and strike. The grade system was subsequently applied to samples obtained from some thirty shallow boreholes put down to investigate in detail the Upper Lias in the central part of the dam site.

Disturbed Upper Lias occurs beneath strongly cambered Northampton Sand in old clay pits near Wellingborough and Irthlingborough (Hollingworth *et al.* 1944, p. 11). The description of rounded elongate lumps of Upper Lias showing original bedding structures, but with possible rotation, being set in a clay matrix is identical to the brecciated texture at Empingham. An essentially similar fabric has been described from the Upper Lias at Wothorpe, near Stamford (Chandler 1972), where it was presumed to result from the growth and subsequent melting of ground ice lenses associated with permafrost conditions. At Empingham the Upper Lias appears to have been similarly brecciated to depths of at least 20 m in the central part of the valley. The 'limit of brecciation' shown in figure 6 marks the approximate lower boundary of the disturbed fabric in which the remoulded matrix forms more than 25 % of the Upper Lias. This boundary is far from precise and zones of severe and slight brecciation are sometimes juxtaposed. Evidence of slight brecciation has been observed at depths of up to 30 m. The zone of brecciated Upper Lias persists beneath the Inferior Oolite, but as it is traced away from the valley bottom the thickness of brecciated Lias gradually decreases as the thickness of the Inferior Oolite cover increases. Thus at borehole SD6 there is about 9 m of brecciated material beneath 13 m of Inferior Oolite, while upslope, in the dam cut-off extension trenches, brecciated material occurs beneath some 16 m of Inferior Oolite. There are signs of appreciable brecciation in the Upper Lias to about the same depths below existing ground level at all points on the camber slopes although, with the increase in thickness of the overlying Inferior Oolite in the upslope direction, the depth of penetration of the disturbance into the Upper Lias is correspondingly diminished.

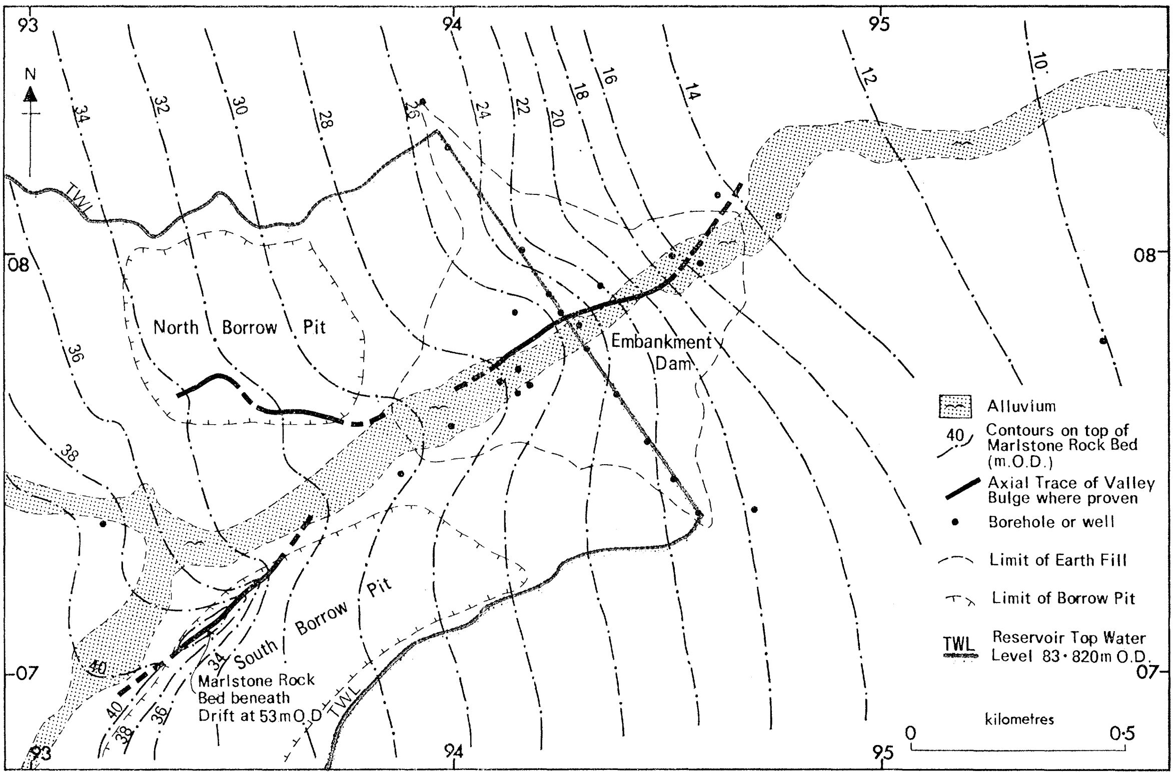

FIGURE 7. Location of valley bulge structures near the Empingham Dam site.

Brecciation has apparently increased the permeability of the Upper Lias (Chandler 1974). *In situ* tests at Empingham show a steady increase in permeability from a range of 1×10^{-12} to 1×10^{-11} m/s at depths of 18–20 m at a range of 8×10^{-10} to 1×10^{-10} m/s at depths of 2–4 m. Generally, therefore, the least disturbed Lias is also the least permeable although the beds within 10 m of the top of the Marlstone Rock Bed are apparently sufficiently well jointed to exhibit much higher bulk permeabilities. Ground water under artesian pressure in the Marlstone Rock Bed was able to flow through these beds in sufficient quantity to flood quickly a shaft excavation in the Upper Lias although the floor of the shaft was at the time still some 15 m above the top of the Marlstone Rock Bed. Significantly, the site was also close to an area of valley-bulging.

The form of the 'limit of brecciation' is comparable with that of the valley topography above. This suggests that the forces which produced the brecciation must have extended down from an old valley surface. The probable mechanism was permafrost but there is, unfortunately, no evidence as to the manner in which ground ice may have developed in what was originally a relatively impermeable formation.

6. Valley bulging

Valley bulge structures have been recognized at a number of places throughout the Empingham Reservoir site (figure 4). The most detailed observations were made at the foundation excavations at the dam site and from the nearby North and South Borrow Pits. At the dam site, mapping of the outcrops of the marker beds within the Upper Lias, in particular the Pisolite Bed and the Ammonite Nodule Bed (figure 6), showed that the beds had been folded into a complex anticlinorium with overfolding and shearing. The anticlinorium was mapped over a distance of 520 m along the valley at the dam site and its approximate position beneath drift deposits inferred from boreholes, trial pits and deep excavations for a further 350 m downstream and 120 m upstream (figure 8). Individual folds in the marker beds could be traced for distances of up to 80 m laterally and the shear surfaces in the clay were often continuous for distances of up to 50 m. Usually these shear surfaces dip away from the bulge axes and frequently lie close to the boundaries of the more competent marker beds, particularly the Pisolite Bed and the Ammonite Nodule Bed (figure 2). Micropalaeontological study of material from borehole DG6 in the centre of the bulge zone has shown that only Foraminiferal Assemblage Zones I to III are present at this point and that there is some repetition of Assemblage Zones II and III above the Pisolite Bed (Coleman & Horton 1972). This suggests overfolding or thrusting, thereby confirming the evidence of the field mapping.

Sections incorporating both surface and subsurface information are shown in figure 6 Section 6B is drawn on the dam centre line and section 6C is 75 m downstream, both to natural scale. In both sections the axis of the valley bulge lies close to the floor of the valley, although it does not necessarily lie within the limits of the modern flood plain. The valley bulge structure in this area is essentially a narrow zone of highly disturbed strata about 100 m in width, beyond which the marker beds, although displaced, are only gently upwarped. The underlying Marlstone Rock Bed and the basal Upper Lias Fish Beds Member are largely unaffected by the bulging although structure contours based on boreholes in the vicinity suggest an updoming in these beds of about 2 m. The bulge structure is sharply truncated by the base of the Head and by the flood plain alluvium, so that the theoretical maximum amplitude of the anticlinorium cannot be assessed accurately. The maximum demonstrable vertical displacement of the Pisolite Bed in these sections is about 15 m, while the presence of mudstones with coarse *Chondrites*-type mottling from the upper part of the Cephalopod Limestone Member in the core of the bulge at outcrop suggests vertical displacements of these beds in the order of 18 m. An isolated outcrop of the Pisolite Bed in a temporary excavation at the downstream toe of the dam indicates an upward displacement of this horizon by at least 25 m there. The tentative reconstructions of the bulge structure in the sections suggest an overall horizontal shortening of at least 60 m. The upper part of the valley bulge structure may have been subject to erosion as it continued to form so that the actual upward displacement probably exceeds the total measured uplift of the Upper Lias. One or more planes of décollement must presumably be present below the bulge structure to accommodate the horizontal movements. In borehole DG6 the bedding is clearly disturbed by folding and faulting (as well as by permafrost brecciation) to a depth of about 2 m above the nodular limestone in the Cephalopod Limestones Member (see figure 2) where the bedding dip becomes more or less horizontal. It seems possible that a plane of décollement occurs at about this level in this area.

Valley bulge structures were also observed in the North and South Borrow Pits (figure 7). In the North Borrow Pit the axis of the valley bulge followed a rather sinuous course westwards from the upstream toe of the dam and could be traced for about 500 m. The axis of the bulge lay up to 300 m outside the limits of the modern floodplain. The Marlstone Rock Bed and the Fish Beds Member were apparently not affected by the valley bulge structure in this area; in the South Borrow Pit, however, both the Marlstone Rock Bed and the Fish Beds Member were exposed in the core of the bulge for distances of 33 and 70 m respectively. Clearly the plane of décollement of the valley bulge in the vicinity of the South Borrow Pit must lie within the Middle Lias Silts and Clays. Bedding dips up to 70° were observed close to the bulge axis. In the area of the Marlstone Rock Bed outcrop the bulge was a relatively simple tight anticline with little subsidiary folding but elsewhere folding and overthrusting of the younger marker beds was evident. The bulge plunged eastwards at about 1 in 20 (3°) and could be traced for about 250 m towards the dam site. Westwards, the structure passed beneath First Terrace clays and sandy gravels. These structures are apparently unaffected by the valley bulging movements.

There is little doubt that valley bulge structures are developed in or close to the valley floors throughout the reservoir basin. Similar structures affecting the Inferior Oolite have been recorded from the entire length of the Gwash valley below Empingham (Hollingworth *et al.* 1944, Plate III). At the head of the reservoir near Oakham, trial pits in the outcrop areas of the Marlstone Rock Bed show gentle dips away from the valleys, suggesting that they lie on the flanks of valley bulges developed in the Middle Lias Silts and Clays somewhere in the valley floors. Elsewhere in the reservoir basin, isolated boreholes and trial pits in the valley floor have encountered steeply dipping Upper Lias, indicating the possible presence of valley bulge structures.

In the axial zones of the valley bulge structures, boreholes show that the beds are brecciated to a depth of about 15 m (figure 6). Although the beds in the valley bulge are steeply dipping or almost vertical the fabric of the brecciated material is essentially the same as that in the valley slopes (p. 436). The brecciated zone extends to a lesser depth below the ground surface in the area of the valley bulge compared to its penetration beneath the adjacent valley slopes. This may result from lithological differences in the rocks affected at the time that brecciation developed. Possibly the stronger beds within the Foraminiferal Assemblages Zones III and IV, which are affected by the bulge at the Empingham dam site, are more resistant to brecciation. Alternatively, and more simply, the lesser depth in the bulged area, may result from rapid down cutting and hence enhanced erosion in the axial region of the valley. However, the increased permeability of these beds within the valley bulge structure would be expected to result in the enhanced development of permafrost and hence of brecciation. How much of the brecciation results from permafrost disturbance and how much, if any, is due to rupture by some other process is uncertain. The abundance of aligned steeply dipping polished shear surfaces in the bulged area indicates that the deformation produced thrust movements along these surfaces. Hence the structure developed by passive failure rather than by brecciation of the Upper Lias with the wholesale disruption of the original bedding. Some small scale movements were no doubt accommodated by internal fracture and rotation, but the integrity of the strata within

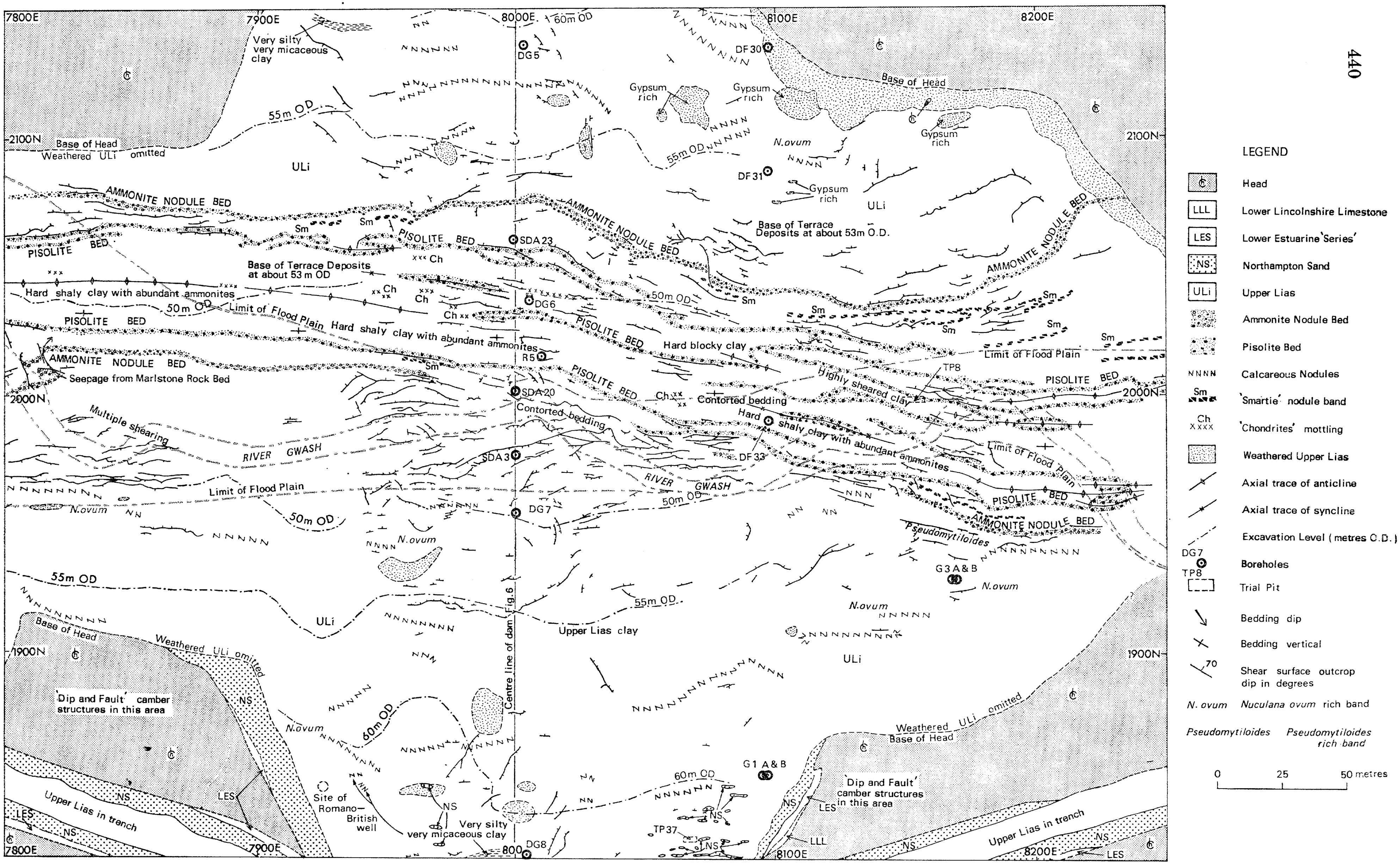

FIGURE 8. Generalized map showing the structure of the Upper Lias in the valley bulge at the Empingham Dam site.

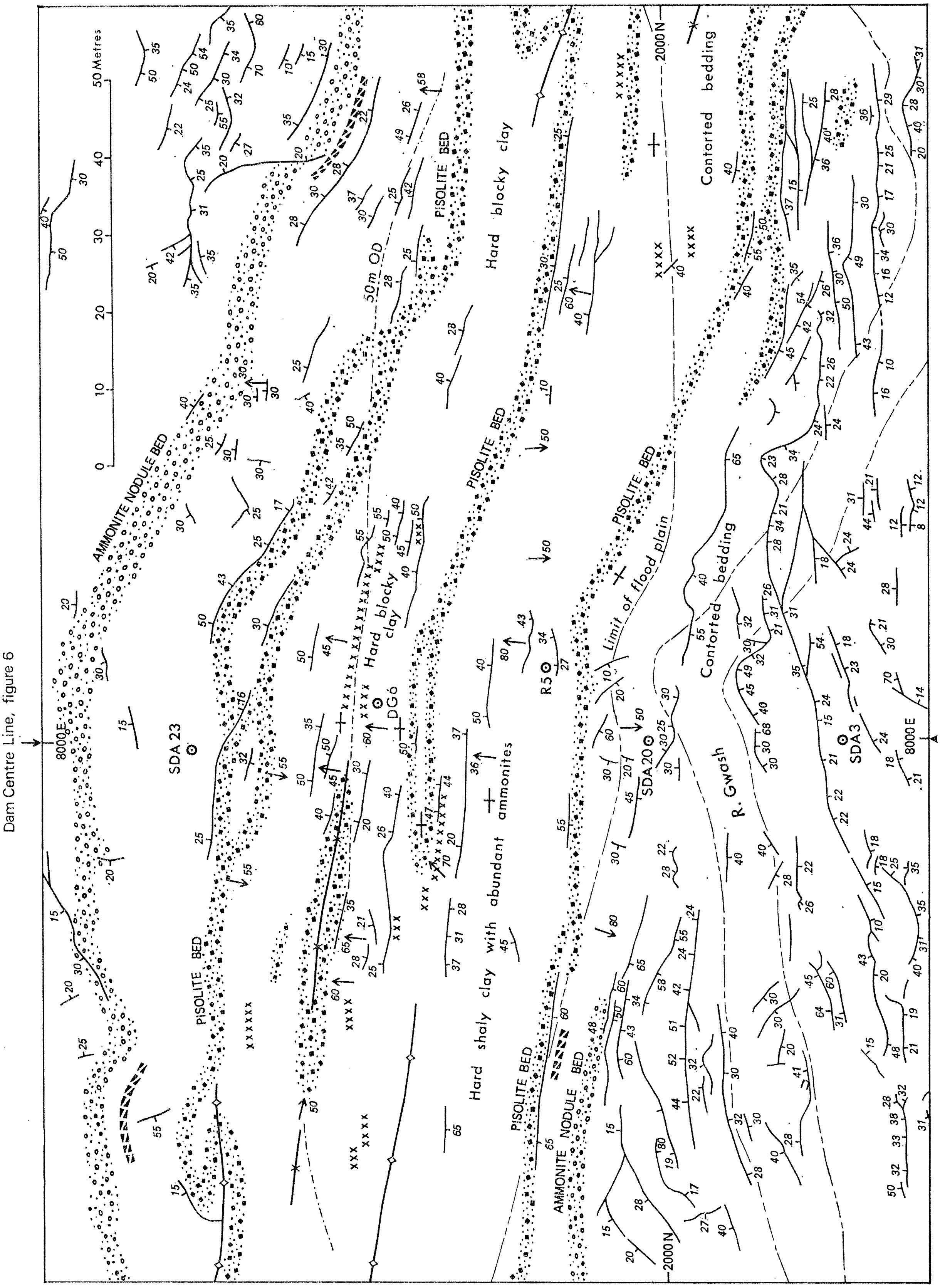

FIGURE 9. Geological plan showing the detailed structure of part of the valley bulge. (Key as figure 6.)

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the bulged zone suggests that their effects were subordinate to shearing and folding. The brecciation thus appears to be mostly due to permafrost and largely pre-dates or is contemporaneous with the main bulging movements.

7. Engineering properties of the Upper Lias

The Upper Lias mudstones encountered in deep boreholes and in tunnel excavations, where the strata are unaffected by cambering, valley bulging and permafrost brecciations, show considerable variation in their physical properties. These variations are to some extent related to stratigraphical horizon. Figure 2 shows the distribution of natural moisture content, plasticity, carbonate content and undrained shear strength in relation to the generalized lithostratigraphic sequence in the Upper Lias. The natural moisture content lies in the range 12–21 % with the driest material generally below the Ammonite Nodule Bed. The Upper Lias is very heavily overconsolidated and as a consequence in its undisturbed state has a moisture content well below its plastic limit. The plasticity index in the upper 25 m lies in the range 36–46 %, but the mudstones at lower stratigraphic horizons are generally rather less plastic with plasticity indices averaging 27 % and falling as low as 16 % near the Marlstone Rock Bed. Despite the evident variations in plasticity, the Atterberg limits plot in figure 2 suggests an essential similarity in the clay mineral content of the Upper Lias throughout its thickness. Clay fractions in the upper 25 m generally lie in the range 35–50 % with activity ratios in the range 0.8–1.3.

Table 2. Engineering properties of Upper Lias at Empingham

	natural moisture content (%)	plastic limit (%)	liquid limit (%)	undrained shear strength† kPa
undisturbed Upper Lias (deep boreholes and tunnels)	12–21	19–28	39–72	50–670
brecciated Upper Lias, unweathered (dam foundation)				
(i) outside Bulged Area	17–27	19–30	50–71	30–200
(ii) inside Bulged Area	18–25	20–24	45–59	30–200

† Triaxial compression tests on 100 mm diameter × 200 mm long specimens, rate of strain 2 % per minute, confining pressure 400 kPa.

X-ray analyses of four samples taken from depths of 31.10–32.80 m below ground level in borehole SD6 and therefore about 16–18 m below the top of the Upper Lias showed a predominance of a layered clay-mineral probably illite with subordinate kaolinite and traces of another clay mineral, possibly chlorite or vermiculite. Other minerals present included pyrite, gypsum, calcite, siderite and quartz. The variation of carbonate content (expressed as calcium carbonate) in borehole B14 at Wothorpe shows a marked increase below about 20 m from the top of the Upper Lias, rising from 2–4 % to about 10 %, with peaks above this figure in the Ammonite Nodule Bed, the Pisolite Bed and the Cephalopod Limestones Member. The downward increase in the mechanical strength of the Upper Lias mudstones, particularly at and below the Ammonite Nodule Bed, is related to changes in the carbonate content suggesting that part at least of the carbonate is acting as a cementing agent.

In the dam foundations area, the brecciated Upper Lias has a higher natural water content than undisturbed material from the same stratigraphic horizon elsewhere. The mean value rises from about 20 % at 20 m below the top of the Upper Lias to about 25 % just below the Northampton Sand. The same general distribution is apparent even wheıe the Upper Lias is mantled only by Head or Alluvium, although in the superficial weathered zone moisture contents up to 35 % occur.

A detailed study of the strength of the Upper Lias clay was made during investigations for the embankment dam. This has been summarized in part by Vaughan, Werneck & Hamza (1973). As is usual with over-consolidated clay, the standard 'quick' triaxial compression tests were found to overestimate the bulk undrained strength of the brecciated clay. The analysis of three slips in temporary borrow pit slopes, the performance of the trial embankment constructed as part of the dam (Vaughan *et al.* 1973) and the results of slow undrained compression tests on 254 mm diameter specimens (Maguire 1975) indicated a bulk undrained strength in the lower part of the valley slope outside the bulge zone varying from 30 kPa at the top of the clay to 80 kPa at 15 m down. Below this depth the strength depended on the local degree of brecciation, reaching about 200 kPa in relatively unbrecciated clay at a depth of 20 m. The undrained strength was anisotropic, with the anisotropy reflecting the relict bedding of the clay.

The peak bulk strength of the brecciated clay in terms of effective stress was measured in undrained compression tests with pore pressure measurements on 254 mm diameter specimens (Maguire 1975). An average result of $c' = 3$ kPa, $\phi' = 23°$ was found. This strength was slightly anisotropic, being a minimum along bedding planes. The drained strength of the unbrecciated clay was not examined specifically. If an angle of internal friction, ϕ', of 23° is assumed, then the undrained strength of this clay from depth (*ca.* 500 kPa) implies a cohesion intercept, c', of the intact clay of the order of 100 kPa. At depth both the bulk drained and undrained strengths would be controlled by the strength and orientation of discontinuities such as fissures. The residual drained strength of the Upper Lias clay at large shear displacements has been determined in the ring shear apparatus (Chandler 1976). The residual friction angle, ϕr, varies from 12–17° at a normal effective stress of 25 kPa to 8–11° at 150 kPa. Various tests performed on samples containing shear planes from the surface of the valley bulge gave a minimum strength on these planes of $c' = 0$, $\phi' = 15°$. This result may reflect the low effective stresses on the surface of the valley bulge. The performance of the trial embankment indicated that a strength of at least $c' = 0$, $\phi' = 14°$, could be mobilized in the sheared foundation with shearing at right angles to the previous slope movement.

8. Origin of superficial structures

Various hypotheses have been postulated for the origin of cambering and valley bulging. Hollingworth and his colleagues who first described them in detail and realized their significance considered that differential unloading resulting from valley down-cutting was a critical factor. Subsequently Kellaway & Taylor (1953) modified the theory by suggesting that the development of permafrost may have been essential to the formation of the structures. Recently Kellaway (1972) has suggested that certain valley bulges are due primarily to glaciation and the subsequent unloading of the ice-sheet with the resulting rebound rather than the growth and decay of ground ice.

From the earliest discussions, Boyd Dawkins (in Sandeman 1920) noted the similarity in style between the valley bulges and the upheave structures (creep folds) produced in the floor of mines and deep excavation where the weak rocks in some workings are squeezed into the excavation. Before such disturbances can arise there must be adequate confining pressures, material of the correct lithological type and suitable water content at floor (or roof) level, and a space into which upheaval can occur. In coal mines the phenomena is widespread but it is most common where the floor consists of soft intensely shattered mudstone seatearths.

Valley bulging and cambering are related processes and have been described from diverse rocks ranging in age from Carboniferous to Pleistocene drift deposits. They are particularly well developed in British Jurassic and Cretaceous sediments which contain thick argillaceous sequences. The rocks affected by valley bulging are intensely fissured and commonly sheared and have obviously been affected by intense pressures which have resulted in upward displacement of the rocks. The differential stresses have caused overthrusting in places. Some structures are symmetrical but others, for example a complex structure consisting of three separate valley bulges exposed in the floor of an Ouse tributary valley (Horton *et al.* 1974) has been produced by lateral pressures into the valley of differing intensity. The inequality between the lateral horizontal pressures has caused a change in mode of deformation of the bulges from overthrusting, to asymmetric folding and finally at the greatest distance from the maximum stress, symmetrical folding.

At Empingham overthrusting has occurred but the main valley bulge structure is a symmetrical anticlinorium. Any theory of origin must explain why the thickness changes lie almost entirely within the Upper Lias at the dam site, why the zone of bulged structure has a trend coincident with that of the modern valley system and why throughout the present Gwash valley the vertical extent of the beds affected broadly follows the thalweg of the modern river, so that when traced downstream the structure extends to rocks ranging from Marlstone Rock Bed to Northampton Sand in age.

It has been suggested that the release of pressure due to the unloading of over-consolidated clays as a result of valley erosion may cause a rebound effect (Peterson 1958). In the Bear Paw Shale, the rebound occurs in two stages, a very rapid elastic rebound followed by a slow progressive adjustment, a swelling or a 'time rebound', which results in the softening of the material as a result of increasing water content, and consequent volume increase caused by expansion and rearrangement of the clay particles. Peterson's experiments suggested that the maximum rebound occurs in the weakest beds, in this example those with the highest water content, and decreases with increasing strength. This example may differ from the Upper Lias where there is no evidence of major change in water content beneath the Northampton Sand cover and away from the zone of surface weathering. That changing water content although facilitating movement, may not be critical is suggested by the upheaval of mine floors.

Valley rebound phenomena appear to be widespread in Central Alberta (Matheson & Thomson 1973). There the release of pressure due to the incision of post-glacial channels causes upwarping of the valley walls with formation of a slightly raised valley rim and a gentle anticlinal flexure in the valley floors. Theoretical models using a homogeneous isotropic solid show that the peripheral uplift is reduced as the ratio of lateral to vertical stress prior to excavation increases. The recorded rebounds are less than 7 m, or generally between 3–5 % of the depth of the valley, but exceptionally attaining 10 % of this figure. There appears to be a relation between this value and the modulus of elasticity of the rocks forming the valley. The upwarping appears to have taken place by interbed movements with the development of weak gouge zones of remoulded material.

The Canadian examples have developed since the last glaciation but stream anticlines, which are comparable in structure to valley bulges, have been described from modern valleys (Simmons 1966). Both are much smaller than the major structures described here and there is strong evidence (p. 434) that the Empingham features have not originated in Recent times.

Valley bulge and camber structures occur in glaciated and periglacial regions. In the East Midlands some valley bulge structures predate the main glaciation (Chalky Boulder Clay glaciation) of the region (Rice 1962), while others were formed after this ice-sheet retreated. The recognition of cambering in drift deposits with typical 'dip and fault' structures is additional proof that the structures developed in later Pleistocene times. The occurrence of cambered Handborough Terrace gravels indicates that the process was continuing in post-Chalky Boulder Clay times in Oxfordshire, in an area beyond the limit of glaciation (Kellaway, Horton & Poole 1971). On the other hand the bulging at Empingham pre-dates the First Terrace deposits, which are probably of mid-Devensian age.

The cambering process appears to have been at its acme during the cold period of the Chalky Boulder Clay glaciation. No comparable structures have been unequivocally dated to the last glaciation, the Devensian. The process has certainly not continued in historic times.

It is possible that many superficial structures were initiated during the period of rapid downcutting which preceded the glacial epochs (Horton 1970, p. 27). This overdeepening would cause rapid but localized rebound. Other geological processes may have produced the same result. Thus differential erosion may have resulted from the advance of an ice sheet across an already overdeepened terrain. The weight of a continental ice-sheet would exert increased pressures on the underlying rocks. The development of subglacial drainage channels along the lines of a pre-existing drainage system would result in continued erosion and increased heave in the valley floors as a result of the increased ice load, in association with the tunnel-valley cavity. The variation in thickness of the ice blanket would result in differing overburden pressures being imposed on the rocks lying in a plane lying below valley level. The process of differential rebound may have been greatly enhanced by the growth and decay of ground ice which resulted in a net vertical displacement of the sediments within the permafrost zone.

All these glacial and periglacial processes would be secondary features which, if active, would enhance the rebound phenomena which resulted from localized overdeepening. Thus at Empingham rapid downcutting of a proto-Gwash drainage system is believed to have led to the release of high horizontal stresses in the heavily overconsolidated Upper Lias resulting in predominantly lateral strains in the valley sides and consequential lowering of the ground surface in these areas. The maximum strains would occur in the weaker clay formations, the limestones of the Middle Jurassic forming more rigid blankets. The maximum lateral displacement would occur at outcrop and as material was removed by erosion in the valley floor more would be translated valleyward, while the lowering of the valley sides would lead to the development of camber structures in the rocks of the Inferior Oolite. The Marlstone Rock Bed was presumably sufficiently strong and deeply buried at Empingham to be unaffected by the release of stress. In consequence, décollement would occur at about this level, or above the slightly less rigid Fish Beds Member. The possible mechanisms are discussed in detail in the Appendix by Dr P. R. Vaughan. He finds that the thinning of the strata observed at

Empingham greatly exceeds the theoretical thickness reductions based on the calculated stress relief due to erosion. It is probable that the presence of permafrost or of ice-sheets would probably have greatly accentuated the growth of these structures.

9. The present-day valley

The present erosional cycle was initiated long before the development of the superficial structures. Kellaway & Taylor (1952) suggest that the predominantly west to east flowing River Welland and its tributaries originated as a consequent drainage system developed upon an easterly tilted pre-Pleistocene surface. This surface cut across diverse Jurassic formations and is thought to have resulted from a late Tertiary period of marine peneplanation. Whatever its original form, a deeply dissected landscape was already in existence in the East Midlands at the time of the Chalky Boulder Clay glaciation† (Horton 1970; Wyatt 1971). During the early stages of this glaciation, before the arrival of the ice-sheets in the East Midlands, some of the valleys were greatly overdeepened (Horton 1970). By the end of the glaciation the whole district was blanketed with drift and probably most, if not all, the valleys were blocked. On the retreat of the ice many of the major rivers re-excavated their former courses though small diversions and the cutting of new channels occurred locally. In these cases the new rivers have commonly not excavated the whole of their drift-filled valleys (Horton 1970). Elsewhere entire valleys may remain blocked (Rice 1962; Wyatt 1971; Wyatt, Horton & Kenna 1971).

Around Empingham the glacial deposits have been largely eroded away. Remnants of the once extensive boulder clay are now restricted to the hill summits and pockets occurring within gulls. These deposits generally lie above 98 m O.D. in the vicinity of the reservoir. The nature of their basal surfaces is insufficiently well known to determine the nature of the preglacial land surface. However, the presence of drift-filled cols within the Inferior Oolite south of the reservoir is evidence of some pre-existing topography. It has already been suggested (p. 445) that the cambering process may have been initiated before the deposition of the Chalky Boulder Clay and therefore it is probable that a pre-glacial depression existed along the valley of the Gwash. Extensive glacial deposits are absent from the present valley but they occur within the gulls of the cambered strata. The emplacement of the Chalky Boulder Clay appears to have taken place after the development of the gulls thus indicating that a valley existed before the ice-sheet reached the area (figure 11).

After the retreat of the Chalky Boulder Clay ice-sheet the district was not glaciated again. There are no deposits preserved in the valley which represent the long interval between this glaciation and the deposition of the river gravels. The latter form terrace features ranging in height from 1.5 to 3.5 m above the flood plain. The base level of the terrace gravels is generally 2.5–3.5 m above the base of the modern alluvial gravel. An elephant tusk was found in the spoil from the South Borrow Pit and probably originated in the thin deposit of First Terrace gravel which there caps the Upper Lias (figure 1). The tusk is older than 42600 years B.P. (SRR 834-IGS/179). At least two terraces are developed in the valleys of the main Fenland rivers but with an isolated exception apparently only the youngest is developed in the Gwash valley,

† The Chalky Boulder Clay glaciation is generally thought to be of Wolstonian age (Mitchell, Penny, Shotton & West 1973), but in East Anglia lithologically identical and possibly coextensive boulder clays underlie Hoxnian Interglacial sediments and are therefore of Anglian age (Bristow & Cox 1973).

the river gravels probably equating with the First Terrace of the Welland. An erosional bench, the Hambleton Surface, can be traced intermittently through the valley and it has been suggested that this was formed during the erosional phase associated with the formation of the Second Terrace of the River Welland (Chandler 1976). Locally the terrace gravels have partly eroded the weathered Upper Lias to rest on fresh mudstones. These gravels are succeeded by Head deposits (figure 10).

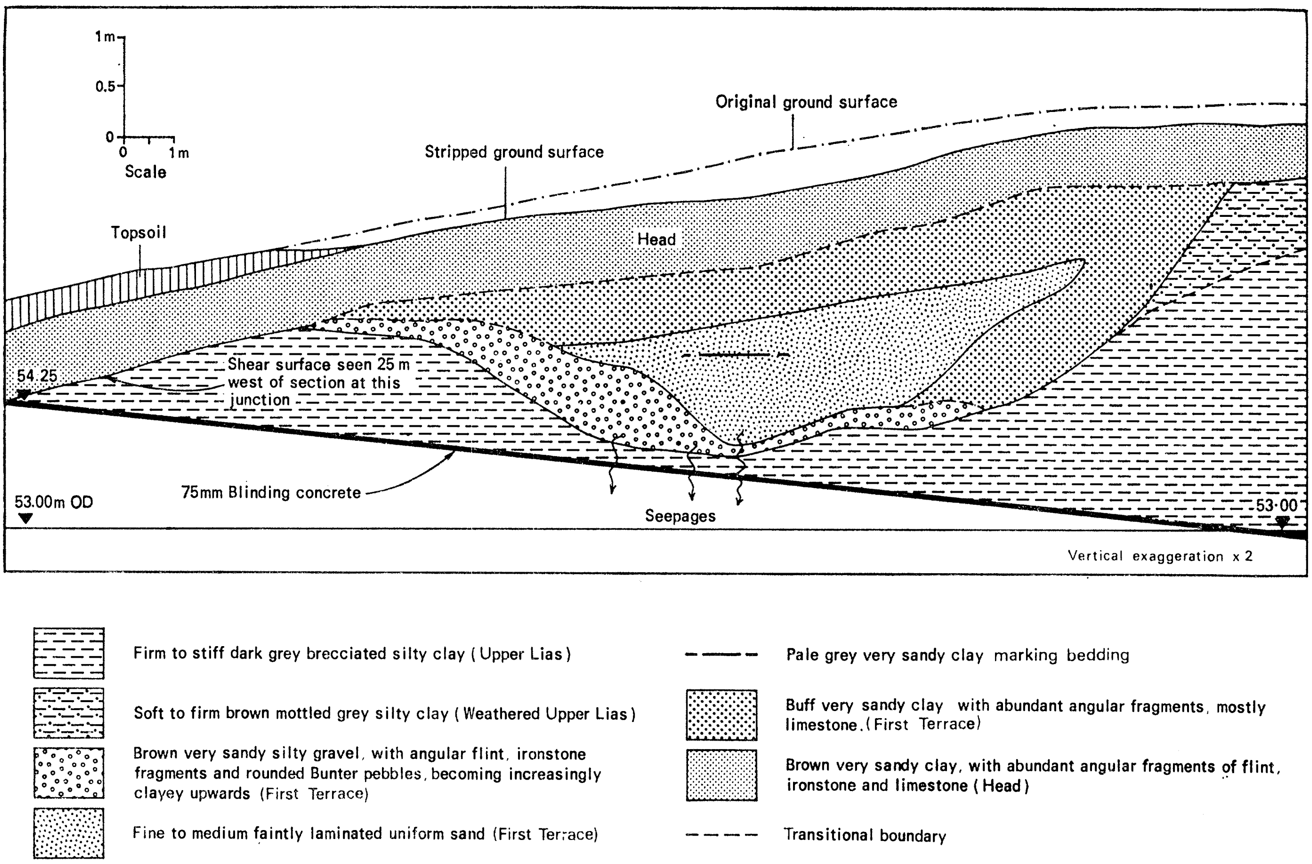

FIGURE 10. Section showing the relation between the First Terrace and the Head at the Empingham Dam site.

Fluviatile erosion has been the dominant factor in the development of the present land forms in the valley of the River Gwash. The close relation between the axial trend of the modern valley and that of the valley bulge structures shows that the erosional processes have continued to be most active along much the same course during the very long interval since the superficial structures were initiated. The upstream displacement of the present alluvial tract in relation to the confluence of the valley bulge structures (figure 7) shows that downcutting was associated with headward erosion. Contemporaneously the valley was being widened by landslipping, solifluxion and hill wash. The relative effect of these processes are dependent upon the nature of the formations cropping out on the valley slopes.

Downstream of the dam site the valley narrows where it crosses the Inferior Oolite outcrop and where cambering brings the resistant rocks near to the valley floor. The rocks in the floor are bulged. Hereabouts the valley slopes were probably developed by solifluxion and soil creep.

Where the Upper Lias crops out above alluvial level landslipping may occur and an example, possibly of rotational type, occurs near Empingham where an over-steepened slope has been cut in the Lias.

At the dam site extensive cambering brings the Inferior Oolite down towards the valley floor. The valley slopes are mantled by up to 1 m of Head so that the Upper Lias outcrop is restricted to a narrow zone close to the flood plain. The Head consists of debris derived from the formations occurring further up the slope. The cambered Lincolnshire Limestone is abruptly overlain by up to 1 m of granular Head consisting of angular limestone fragments (up to 0.05 m) in a clayey matrix. Although the Head maintains its thickness across gulls and cambered blocks it may change in composition according to the parent material within these structures. Thus where Lincolnshire Limestone Head spreads across a Chalky Boulder Clay-filled gull within the Limestone country rock, it gives way downslope to Boulder Clay Head (figure 11), which forms a tongue extending a short distance below the gull outcrop before being enclosed by the Limestone Head. Further downslope the Head changes as it crosses the outcrop of the Lower Estuarine 'Series' and Northampton Sand.

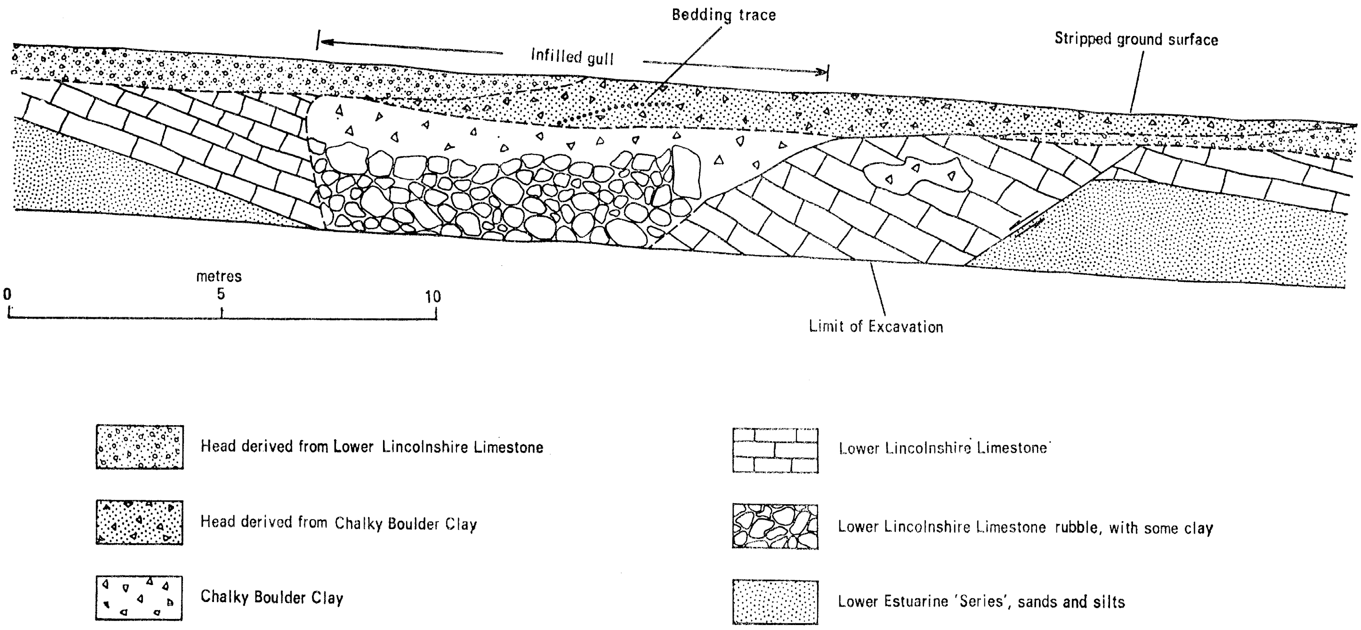

FIGURE 11. Section in the west side of a pipeline trench from chainage −270 to chainage −298 m, showing the nature of a gull infilling and the development of Chalky Boulder Clay Head.

The Head deposits derived from the Inferior Oolite formations give rise to a single sheet deposit. Shear surfaces have not been recognized within or at the base of this Inferior Oolite Head when it overlies the parent formations. This type of Head probably moved downhill by a process of solifluxion (soil creep) largely in response to alternate freezing and thawing, though rain wash may have been a contributary factor. Mr P. Horswill notes that in most sections the boundaries of the Chalky Boulder Clay Head are abrupt and hence that it moved as a distinct mass within the enclosing Lincolnshire Limestone Head. He believes that the present ground surface of the deposit is an erosional level the overlying zone where the Head deposits merge having been removed by erosion. Mr A. Horton believes that the apparent limited downslope spread of the Chalky Boulder Clay Head probably marks the limit beyond which the parent material becomes so mixed with the Lincolnshire Limestone Head that it can no longer be recognized as a distinct unit. Similarly the soft fine-grained sediments of the Lower Estuarine 'Series' do not contain any indurated fragments or distinctly coloured material which would give rise to a readily discernible Head lithology. The Lincolnshire Limestone Head gives way abruptly to the Northampton Sand type and it is possible that carbonate leaching may be very active in the more arenaceous type. The Northampton Sand Head spreads onto the Upper Lias and progressively incorporates clay material. In this state the Head becomes sufficiently cohesive to be subject to movement by translational sliding and small subparallel shears have been recorded at its base (Dr R. J. Chandler 1975, personal communication). The parallel character of the base of the Head and the present ground surface suggests that the latter represents the upper limit of aggradation rather than an erosional surface superimposed on a pre-existing deposit. At the upstream toe of the dam [9388 0748] a thin sequence of bedded sandy clays and clays occurs at the foot of the valley slope at a level comparable with the First Terrace deposits. These probably accumulated by a combination of rain wash, solifluxion and mud flow and may have originated as a translational slab-slide.

Upstream, landslipping becomes increasingly important as the base of the Inferior Oolite becomes much higher relative to the flood plain. The Inferior Oolite is still cambered and strong springs issue at the base. These soften the near-surface Lias and enhance the probability of downslope movement. In these areas rapid downcutting would overdeepen the Upper Lias slopes and facilitate the development of both rotational and translational landslips.

The final stages in the evolution of the Gwash valley were associated with the development of landslips. This type of failure is facilitated when the climate is either wet or cold or both. It is probable that landslipping occurred throughout the Pleistocene but the most recent major phase of movement probably dates from the closing stages of the last, the Late Devensian Glaciation. The slopes have remained relatively unchanged since then. Many of the slopes are blanketed by Head which probably originated under the periglacial conditions which existed at this time, but a little may have continued to form and very slowly move downhill during subsequent cool phases. The discovery of a fossil soil in borehole DG8 [9438 0768] (figure 6) indicates the continuing nature of the Head formation process. The soil has been dated at 3409 ± 60 years B.P. (SRR 119, IGS-EK/22) and occurred at 1.68 m depth beneath reddish brown clay with local rocks and some Bunter pebbles and overlay 0.38 m of sandy clay with only rare pebbles. The fossil soil occurs near an archaeological site and it is possible that human activity may have facilitated the downslope movement of the upper Head deposits. The fossil soil is of very limited extent and occurs in a gulley and it is possible that it postdates the greater part of the lower granular Head which is widespread in the dam area and that soilwash was a major depositional agent for the overlying sediment. The distribution of the upper Head deposit is uncertain and it may be of only limited extent. Both Head deposits predate the alluvium. A bone from the basal alluvial gravel in trial pit TP8 [9441 0790] (figure 8) at 3.3 m depth gave a radiocarbon date of 2945 ± 240 B.P. (St 3757, IGS-C14/85) while wood at 2.4 m depth was 1470 ± 100 B.P. years old (St 3689, IGS-C14/84). Although the upper Head is of Recent age it is possible that the underlying deposits may be of late Devensian age (R. J. Chandler 1975, personal communication).

Some evidence of the shallow instability of the Empingham slopes is afforded by the deformation measured in a 5 m deep Romano-British water well encountered in the dam foundation area [9431 0765] (figure 8). The well had been excavated through cambered Inferior Oolite and a short distance into the underlying Upper Lias. It contained pottery which could be dated on archaeological evidence at A.D. 250–270 while a nearby and presumably contemporaneous building was dated as later than A.D. 200 on the basis of pottery found in a ditch below its foundations (Gorin 1975, personal communication). The well is therefore probably early 3rd century A.D. On the assumption that it was originally built vertically with a circular cross section, the well now shows deformations from its position at ground level of up to 200 mm in a northeast direction, the maximum displacement occurring at a depth of 3 m. The ground slopes north-northeast in the vicinity so the well now had downslope inclination in relation to its top, thus indicating that although cambering has ceased, some potential for valleyward movement may still exist in the present slopes.

The Empingham dam is owned by the Welland and Nene River Division, Anglian Water Authority, whose permission to publish this paper is gratefully acknowledged. The authors wish to thank in particular Dr R. J. Chandler who has maintained a close interest in the field work and generously augmented the authors' observations with unpublished data of his own, and Professor J. Knill who was instrumental in initiating a research contract by the Institute which lead to the discovery of the nature of the thinning of the Upper Lias. The authors are indebted to Messrs T. and C. Hawksley for providing facilities at their Empingham Office and encouragement during the work. Finally they wish to acknowledge the numerous discussions with their colleagues, particularly Messrs G. W. Green and R. J. Chandler.

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References (Horswill & Horton)

Bate, R. H. & Coleman, B. E. 1975 Upper Lias Ostracoda from Rutland and Huntingdonshire. *Bull. Geol. Surv. Gt Br.* **55**, 1–42.

Bristow, C. R. & Cox, F. C. 1973 The Gipping Till: a reappraisal of East Anglian glacial stratigraphy. *Jl geol. Soc. Lond.* **129**. 1–37,

Chandler, R. J. 1972 Lias Clay: weathering processes and their effect on shear strength. *Géotechnique* **22**, 403–431.

Chandler, R. J. 1974 Lias Clay; the long-term stability of cutting slopes. *Géotechnique* **24**, 21–38.

Chandler, R. J. 1976 The history and stability of two Lias clay slopes inthe upper Gwash valley, Rutland. *Phil. Trans. R. Soc. Lond.* **283**, 463–491.

Coleman, B. E. & Horton, A. 1972 A stratigraphic and micropalaeontological study of a valley-bulge structure at the Empingham Dam, Rutland. Unpubl. Rep., Institute of Geological Sciences.

Hollingworth, S. E., Taylor, J. H. & Kellaway, G. A. 1944 Large-scale superficial structures in the Northampton Ironstone field. *Q. Jl geol. Soc. Lond.* **100**, 1–44.

Hollingworth, S. E. & Taylor, J. H. 1951 The Mesozoic Ironstones of England. The Northampton Sand Ironstone: stratigraphy, structure and reserves. *Mem. Geol. Surv. Gt Br.*

Horton, A. 1970 The drift sequence and subglacial topography in parts of the Ouse and Nene basin. *Rep. No.* 70/9, *Inst. Geol. Sci.*

Horton, A. & Coleman, B. E. (In press) The lithostratigraphy and micropalaeontology of the Upper Lias at Empingham, Rutland. *Bull. Geol. Surv. Gt Br.* **62**.

Horton, A., Shephard-Thorn, E. R. & Thurrell, R. G. 1974 The geology of the new town of Milton Keynes. *Rep. No.* 74–6, *Inst. Geol. Sci.*

Kellaway, G. A. 1972 Development of non-diastrophic Pleistocene structures in relation to climate and physical relief in Britain. *Rep. Int. Geol. Congr., 24th Sess. Montreal* **12**, 120–146.

Kellaway, G. A. & Taylor, J. H. 1953 Early stages in the physiographic evolution of a portion of the east Midlands. *Q. Jl geol. Soc. Lond.* **108**, 343–375.

Kellaway, G. A., Horton, A. & Poole, E. G. 1971 The development of some Pleistocene structures in the Cotswolds and Upper Thames Basin. *Bull. Geol. Surv. Gt Br.* **37**, 1–28.

Maguire, W. M. 1975 The strength and deformation characteristics of brecciated Upper Lias clay. Ph.D. Thesis, University of London.

Matheson, D. S. & Thomson, S. 1973 Geological implications of valley rebound. *Can. J. Earth Sci.* **10**, 961–78.

Mitchell, G. F., Penny, L. F., Shotton, F. W. & West, R. G. 1973 A correlation of Quaternary deposits in the British Isles. *Geol. Soc. Lond. Spec. Rep.* no. 4, 99 pp.
Peterson, R. 1958 Rebound in the Bearpaw Shale, Western Canada. *Bull. Geol. Soc. Am.* **69**, 1113–24.
Rice, R. J. 1962 A drift-filled valley at Thistleton on the Rutland–Lincolnshire border. *Geol. Mag.* **99**, 468–74.
Sandeman, E. 1920 The Derwent Valley waterworks. *Min. Proc. Inst. Civil Eng.* **206**, 152–220.
Simmons, G. C. 1966 Stream anticlines in Central Kentucky. *Prof. Pap. U.S. geol. Surv.* 550–D, D9–11.
Vaughan, P. R., Werneck, M. L. G. & Hamza, M. M. 1973 Discussion. In *Symposium on Field Instrumentation in Geotechnical Engineering*, pp. 617–23. London: Butterworth.
Walbancke, H. J. 1972 Empingham Reservoir. Dam foundation. Structural geology. Unpublished Report to T. and C. Hawksley.
Wyatt, R. J. 1971 New evidence for drift-filled valleys in north-east Leicestershire and south Lincolnshire. *Bull. Geol. Surv. Gt Br.*, **37**, 29–55.
Wyatt, R. J., Horton, A. & Kenna, R. J. 1971 Dirft-filled channels on the Leicestershire–Lincolnshire border. *Bull. Geol. Surv. Gt Br.*, **37**, 57–79.

Appendix: The deformations of the Empingham valley slope

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1. Introduction

The detailed subsurface exploration of the sides of the Gwash valley at Empingham, together with the subdivision of the Upper Lias into assemblage zones, has allowed the structure of the west valley slope to be established (figure 6). The purpose of this Appendix is to examine the magnitude of the strains and displacements implied by the present valley slope, and to consider numerically some of the alternative mechanisms which may have caused them. Lateral movements due to stress relief, vertical loading due to overlying ice, and downslope sliding of frozen ground are considered in turn. The calculations presented relate specifically to the Empingham slope and any conclusions which can be drawn may not be valid for all slopes.

2. Strains and displacements of the valley slope

A simplified section of the valley slope is shown on figure A1, plotted at a distorted scale of 4:1. The Upper Lias clay is divided into 3 units, an upper layer (assemblage zones IV and V) a middle layer (assemblage zones II and III) and a basal layer (assemblage I), which is assumed to have remained unstrained. The vertical strains of the two upper layers are estimated from their present thickness and an initial thickness assumed to be that existing at 1000 m from the valley centre line. An average horizontal strain ϵ_h has been estimated from each layer from the vertical strain, ϵ_v.

$$\epsilon_h = -(\Delta V/V + \epsilon_v)/(1+\epsilon_v), \tag{1}$$

where $\Delta V/V$ is a volumetric strain due to decrease in stress and swelling, assumed to vary from 0 at 1000 m from the valley centre line to 0.05 (expansion) at the centre line. The influence of volumetric strain on the horizontal strain is small. The horizontal strains are then integrated to give the average horizontal displacement of each layer, as shown on figure A1. Displacement vectors have then been constructed, and are shown on the section at the distorted scale. The vectors show the movements of originally vertical sections to their present positions.

As the layer of clay between the Pisolite Bed and the Marlstone Rock Bed has been thrust into the valley bulge, the average horizontal displacement of this layer can be estimated separately from the volume of clay present in the valley bulge and that estimated to have been removed by erosion. The vector representing this displacement is also shown on figure A1. It is consistent with the displacements deduced independently from the vertical strains.

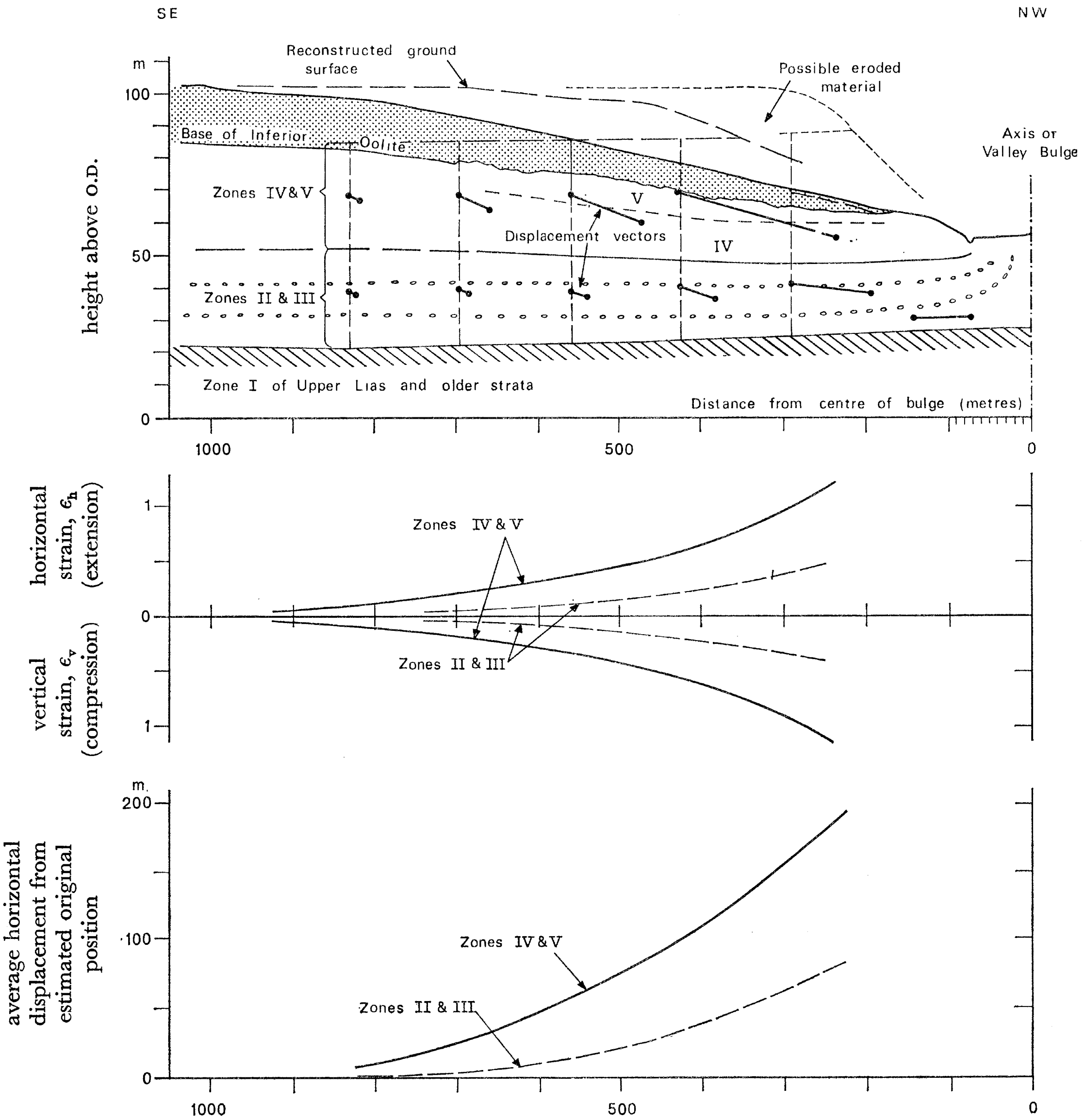

FIGURE A 1. Strains and displacements within the Empingham Slope.

The reconstruction of the undistorted shape of the valley is only of first order accuracy, but it is doubtful if the information available warrants a more sophisticated treatment. The reconstruction is sufficiently accurate to lead to the following conclusions:

(*a*) Strains in the slope are very large, approaching unity.

(*b*) Valleyward displacement of the Upper Lias is also very large, approaching 100 m near the base and 200 m at the top of the formation.

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(*c*) The strains and valleyward movements decrease consistently with depth below present ground surface and they become small at a depth between 30 and 40 m. This implies valleyward tilting of up to 60°, which is in the same direction as that observed in the blocks of overlying strata. Brecciation also decreases with depth, becoming muted at about 20 m but observed down to at least 30 m. Thus there is some correlation between magnitude of movement and amount of brecciation.

(*d*) There must have been substantial shearing on a discontinuity close to the Marlstone Rock Bed.

(*e*) The original valley slope implied by the reconstruction is of the order of 10:1 (6°), but it may have been steeper, with the extra material lost by erosion from the slope surface or by erosion after horizontal movement into the valley bulge.

(*f*) Substantial erosion of material from the bulge zone during slope formation is, in any case, implied. The minimum loss of material is of the order of 3000 m^3 per metre length of valley, and it is mainly of clay from above the Ammonite Nodule Bed. It seems likely that this erosion was concurrent with the evolution of the valley slope.

3. Possible mechanisms causing slope deformation

(*a*) *Relief of high horizontal stress by valley excavation*

The probable existence of high horizontal stresses in heavily overconsolidated clay has been demonstrated (Skempton 1961; Bishop, Webb & Lewin 1965; Brooker & Ireland 1965). In the process of rebound accompanying the removal of overburden pressure the horizontal stress decreases less than the vertical stress, and, if the ratio of previous maximum vertical stress to current vertical stress (the overconsolidation ratio) becomes sufficiently large the clay will fail in shear. The ratio of the horizontal stress to the vertical stress then becomes equal to the limiting passive failure value. High horizontal stresses can cause local failure at the toe of a slope as it is excavated even when the factor of safety against overall slope failure is high (Dunlop & Duncan 1970).

A simple drained analysis reproducing local failure along a shear plane below the valley floor, such as seems to have occurred at Empingham, is shown on figure A 2. A constant water pressure is assumed to operate on the shear plane. This is consistent with a layer of high permeability, such as the Marlstone Rock Bed, underlying the clay. Vertical flow and uniform permeability are assumed between the shear plane and the ground surface, which gives a linear increase of pore pressure with depth.

The total P_x on a vertical plane at distance x from the valley centre line is given by

$$P_x = P_p + S, \tag{2}$$

where P_p is the passive thrust mobilized in the failed bulge zone at the valley centre and S is the total shear force, mobilized over distance x, on the underlying shear plane. If the drained shear strength along this plane is given by $c' = 0$, $\phi' = \phi_1'$, then

$$S = (W-U)\tan\phi_1', \tag{3}$$

where W is the weight of material above the shear plane from 0 to x, $U = h_w\gamma_w x$, and h_w is the head of water above shear plane.

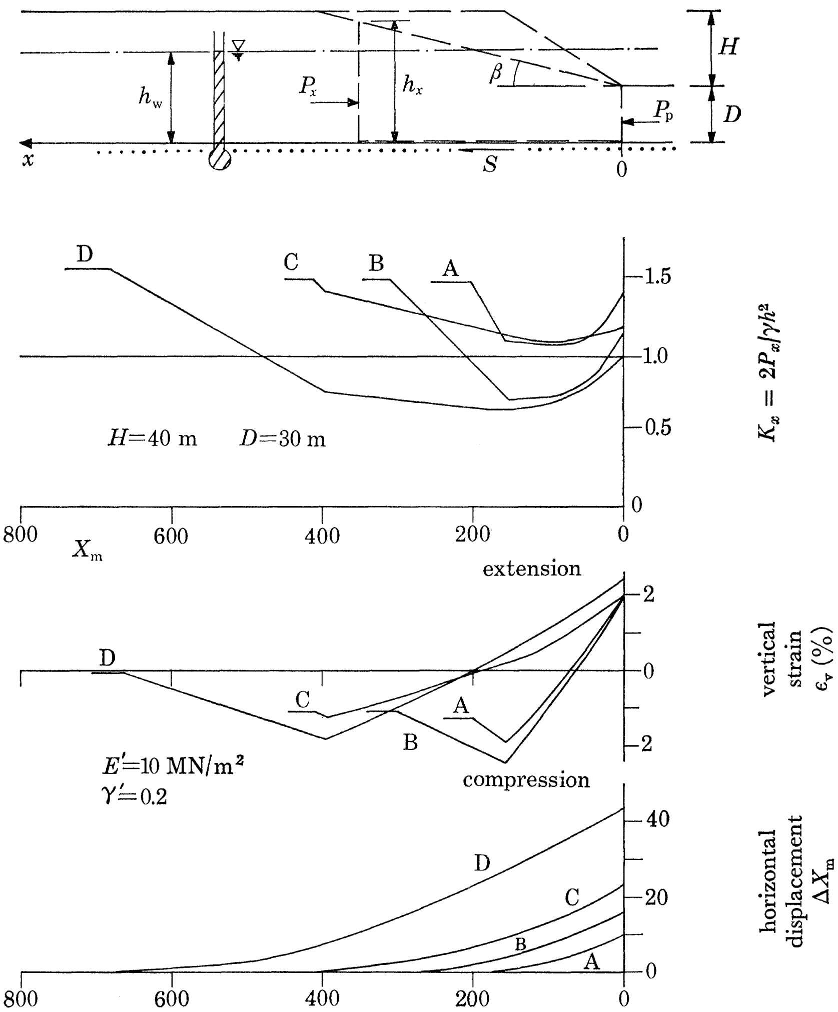
Also
$$P_p = \frac{\gamma D^2}{2}\{K_p(1-r_u)+r_u\}, \tag{4}$$

where γ is the unit weight of clay, D, the depth of bulge zone, r_u, the pore pressure ratio $(u/\gamma z) = h_w\,\gamma_w/D\gamma$, and K_p = Rankine passive earth pressure coefficient.

For a drained shear strength in the bulge zone with $c' = 0$, $\phi' = \phi_2'$,
$$K_p = (1+\sin\phi_2')/(1-\sin\phi_2').$$

The average ratio between horizontal and vertical total stress on the vertical plane at x is K_x^*, and
$$K_x^* = P_x\,2/\gamma h_x^2. \tag{5}$$

The use of equations (1)–(5) gives the maximum value of K_x^* which can exist after valley formation if the mechanism postulated in the analysis develops.



case	cot β	ϕ_1'	ϕ_2'	h_w / m	X / m	Δ_{max} / m
A	4	23	23	40	205	10
B	4	15	15	45	310	16
C	10	15	15	45	415	23
D	10	10	10	60	635	43

FIGURE A 2. Changes in horizontal stress due to valley excavation.

Before valley excavation the maximum horizontal total stress which can exist is controlled by passive failure. With $c' = 0$, this maximum, described by K_0^*, is

$$K_0^* = \frac{1+\sin\phi'}{1-\sin\phi'} - \frac{2\sin\phi'}{1-\sin\phi'}\, r_{u0}; \tag{6}$$

with $\phi' = 23°$ and $r_{u0} = 0.5$ (static ground water with the ground water table at ground level) then $K_0^* = 1.64$. This value is comparable to that estimated to exist in the London Clay (Skempton 1961).

Formation of the valley will lead to a general reduction in seepage pressure, and the value of K_0^* for no horizontal strain remote from the valley will be modified. Since the effective stress will increase, equation (6) will no longer operate. For consistency with subsequent calculations the change in horizontal stress may be deduced from the theory of elasticity, as follows:

With no change in vertical total stress, σ_v,

$$\Delta\sigma_v' = -\Delta u.$$

For no lateral yield

$$\Delta\sigma_h' = \Delta\sigma_v' \frac{\nu'}{1-\nu'},$$

where ν' is the Poisson ratio in terms of effective stress and

$$\Delta\sigma_h = \Delta\sigma_h' + \Delta u$$

$$= \left(\frac{1-2\nu'}{1-\nu'}\right)\Delta u.$$

Hence

$$\Delta K^* = \frac{\Delta\sigma_h}{\sigma_v} = \left(\frac{1-2\nu'}{1-\nu'}\right)\Delta r_u. \tag{7}$$

The extent of horizontal movement due to valley excavation, X, will be that value of x for which

$$K_0^* + \Delta K^* = K_x^*. \tag{8}$$

Values of ν' for overconsolidated clay are typically in the range 0.1–0.3 and a value of 0.2 will be assumed to operate. Hence:

$$K_0^* + \Delta K^* = 1.64 + 0.75\Delta r_u.$$

Values of K_x^*, derived from equations (1)–(8), are shown on figure A2 for two slopes and different values of ϕ' and seepage pressures.

In case A, values of $\phi' = 23°$ are assumed, which approximate to the peak value for the clay (Maguire 1975), together with $h_w = 40$ m, which approximates to the ground water conditions currently observed at Empingham. This case demonstrates that a deep shear plane can develop even if peak shear strength has to be overcome with a low water pressure operating. After failure, a modest amount of movement will cause the strength on the failure surfaces to drop towards the residual value. Cases B and C, for the formation of 4:1 and 10:1 slopes respectively, with $\phi' = 15°$, equivalent to the strength of actual shear planes as observed at Empingham, and with $h_w = 45$ m, a probable value during slope formation, represent situations which would be likely to develop once local failure had occurred. Case D, for a 10:1 slope, with $\phi' = 10°$, equivalent to the lowest possible residual strength, and with $h_w = 60$ m, the highest value permitted by full uplift at the toe of the slope, represents the extreme conditions. The analyses

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demonstrate that, if horizontal stresses approaching passive values exist in the clay prior to valley formation, a passive bulge zone will develop and horizontal extension of the clay beneath the valley sides will occur. However, the predicted extent of this extension only approaches that observed at Empingham if extreme assumptions are made in the analysis.

An approximate estimate of strain and displacement in the valley side may be made as follows:

The stress changes resulting from valley excavation cause unloading and thus linear isotropic elastic theory may be used as a reasonable approximation to relate stress and strain. Assuming plane strain:

$$\epsilon_v = \frac{1+\nu'}{E'}\{\Delta\sigma'_v(1-\nu') - \Delta\sigma'_h\,\nu'\}, \tag{9}$$

$$\epsilon_h = \frac{1+\nu'}{E'}\{\Delta\sigma'_h(1-\nu') - \Delta\sigma'_v\,\nu'\}, \tag{10}$$

stresses may be estimated for any point at depth z and distance x from the centre line by

(*a*) $\sigma_v = \gamma z : \sigma'_v = \sigma_v - u$;

(*b*) $\sigma_h = K^*_x \sigma_v : \sigma'_h = \sigma_h - u$;

(*c*) u is given by the assumed seepage pressures;

(*d*) K^*_x is given by equation (6) before excavation and by equations (5) and (8) after excavation.

The horizontal displacement towards the valley, Δx, is given by

$$\Delta x = \int_X^x \epsilon_h\,\delta x. \tag{11}$$

Values of ϵ_v and ϵ_h for the four cases A–D, assuming $E' = 10$ MN/m² and $\nu' = 0.2$, are shown on figure A 2. $E' = 10$ MN/m² represents a minimum value, approximating to a coefficient of one dimensional volume compressibility, $m_v = 0.1$ m²/MN. A value two or three times greater is more likely, and if this was assumed the strains and displacements would be reduced proportionately.

The results show the following. About 1% vertical thinning is predicted over only a small part of the slope, as compared with thinning over all the slope approaching 100% as observed at Empingham. The predicted cumulative horizontal displacement, Δ, is only about half that observed at Empingham if extreme values of strength, water pressure and compression modulus are assumed. With more likely values the displacement predicted is at least an order of magnitude smaller than that observed. This difference is greater than the likely errors in the simple analysis presented. The nature of the analysis, in which passive failure of the clay prior to valley excavation is postulated, leads to the prediction of deep seated lateral movements throughout the process of valley excavation. This may be demonstrated by analyses at intermediate stages of excavation, with trial failure surfaces at different depths. Since the compression modulus should increase with depth, the analysis suggests that strains and lateral displacements of the clay above the base shear plane should be relatively uniform with depth, rather than diminishing sharply with depth, as observed at Empingham.

In conclusion, the simple analysis of the effects of stress relief due to valley excavation does not reproduce either the magnitude or the distribution of the strains and displacements observed in the Empingham slope at all closely. However, the analysis does show that stress relief could and probably would cause the development of a deep base shear plane at an early stage of valley formation. It also predicts the development of a passive valley bulge, which, while much smaller than that observed at Empingham, would still be a considerable and readily recognizable structure.

(*b*) *Differential vertical loading*

Differential vertical pressures, such as might arise due to a varying ice cover or due to an 'ice tunnel' in the centre of the valley, may be sufficient to cause failure of the underlying strata. Bulging of the strata under areas of low bearing pressure and downward and lateral movement and apparent thinning of the strata under areas of high bearing pressure would then occur. The magnitude and distribution of the vertical pressures required to cause failure

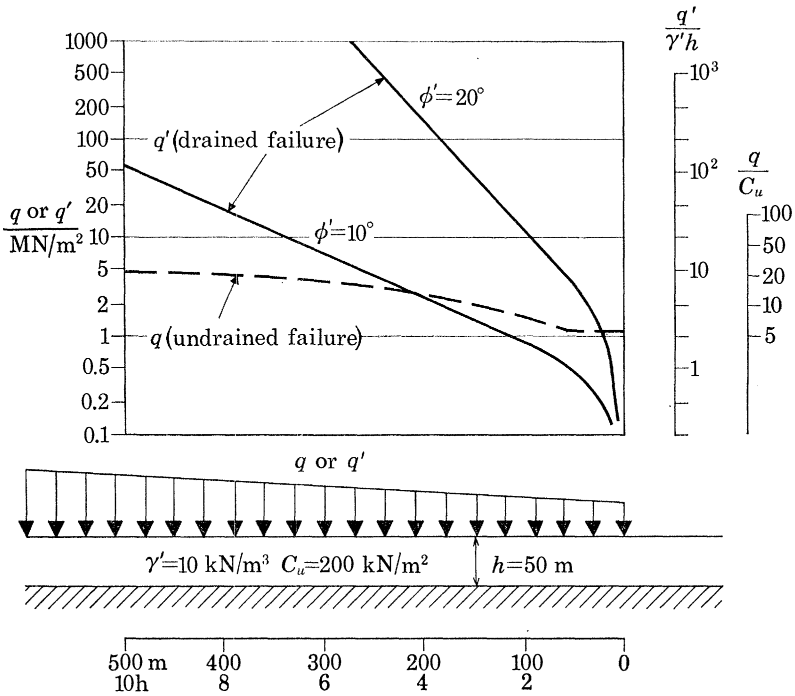

FIGURE A 3. Vertical pressures required to cause yield in a confined clay layer.

if the centre of the valley is unloaded, and the type of movement which would result can be estimated from the theory of Mandel & Salencon (1972). The general solution for the pressures required to cause extrusion of a clay layer compressed between rough loading surfaces is shown on figure A 3, for undrained shear with an undrained strength of C_u, and for drained shear with $c' = 0$, $\phi' = 10°$ or $\phi' = 20°$. Numerical values of the required pressures are shown for a layer thickness of 50 m (the approximate original thickness of the Upper Lias clay) and for a value of $C_u = 200$ kN/m². This is a reasonable value for the undrained strength of the unbrecciated clay. The brecciated clay would be about half as strong and the required bearing pressures would be about half as great. The operational drained strength of the Upper Lias clay at large strains could be expected to be somewhere between 10 and 20°. The results indicate the following:

(*a*) Drained failure other than a very local one requires very high bearing pressures equivalent to 1000–10000 m of ice and this appears to be unrealistic.

(*b*) Undrained failure would occur at much lower pressures. Local failure would require an ice load of the order of 50–100 m and general failure a load of the order of 250–500 m of ice, which are more reasonable values. Loading would have to be rapid (*ca.* 100 years) for undrained conditions to operate, but freezing and thawing beneath the ice might create conditions similar to the undrained state over a much longer time scale. Thus undrained failure under differential pressure is a possibility.

(*c*) Failure would involve slip surfaces in the clay and overlying strata dipping valleyward, and discontinuous movement along these slip surfaces would involve discontinuities in the strata and back tilting of blocks of the strata overlying the clay. The slope section shows no evidence of such movements and the blocks of overlying strata have tipped forward towards the valley and not backwards.

(*d*) The pressure distributions show that as a differential pressure built up, failure would first occur locally in the valley centre. The clay would thin as a result, and this would inhibit failures and thinning of strata further away from the valley centre, even if the pressures increased sufficiently for such failures to be theoretically possible. It is difficult to see how movements of the type predicted could account for the progressive thinning of the strata towards the valley centre which is observed at Empingham.

(*e*) An ice tunnel about 100 m wide would be needed to accommodate the Empingham valley bulge and the stability of a tunnel of this size has not been considered.

In conclusion, differential vertical loading such as might arise from an ice tunnel situation could cause failure of the underlying clay and the formation of a bulge structure. The failure would probably be local and near to the valley centre, however, and there would be diagonal slip surfaces dipping towards the valley. Thus the type of deformation observed in the Empingham slope, with thinning of strata decreasing over 600 m from the valley centre, is inconsistent with the type of deformation predicted from vertical loading.

(*c*) *Slope movements due to ground freezing*

The brecciation of the valley sides at Empingham indicates ground freezing to a depth of at least 30 m below the present ground surface. If the frozen ground was rich in included ice, downslope creep under gravitational loading might have occurred. Shear stresses up to 50 kN/m^2 would have operated.

Movement also may have occurred due to shear in deeper unfrozen ground. If a semi-infinite slope is considered, then stability is governed by the conventional equation

$$\frac{\tan\beta}{\tan\phi'} = 1 - r_u \sec^2\beta,$$

where β is the slope angle.

For material to be removed from the valley slopes, erosion at the centre of the valley must occur. Thus the downslope toe of a mass of sliding frozen ground would be unsupported. Also, there would be a horizontal driving force generated by lateral pressures operating within the frozen ground. If ground freezing is considered as analogous to internal expansion of the clay, then horizontal stresses equal to vertical gravity stresses could develop. Higher horizontal stresses would be relieved by vertical expansion. Horizontal stresses equal to vertical stresses would also develop if there was viscous creep in ice-rich frozen soil.

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The analysis for the semi-infinite slope is modified on figure A4 to include the effect of no support at the toe and horizontal pressures equal to vertical pressures within the sliding mass. As the slope becomes long the modified analysis becomes that for the infinite slope. For the complete Empingham slope the value of d/l would have been approximately 0.05. The analysis predicts the pore pressure required to cause movement. The final slopes at Empingham are at about 4°. The pore pressures required for movement for a 4° slope are $r_u = 0.8$ with peak $\phi' = 23°$, and $r_u = 0.65$ with residual $\phi'_r = 15°$. These pore pressures are greater than hydrostatic and could only exist due to artesian conditions, which are unlikely, or as transient excess pore pressures. Such pore pressures might develop temporarily if melting occurred at depth, with the weight of the frozen ground partly supported by the free water generated by thawing. The existence of high pore pressures beneath frozen ground is suggested by McRoberts & Morgenstern (1974). Thus movements on the flat Empingham slopes could be accounted for.

Shearing might have occurred at varying depths, dependent on the depth of frozen ground. This would be consistent with the decrease in deformation with depth observed at Empingham.

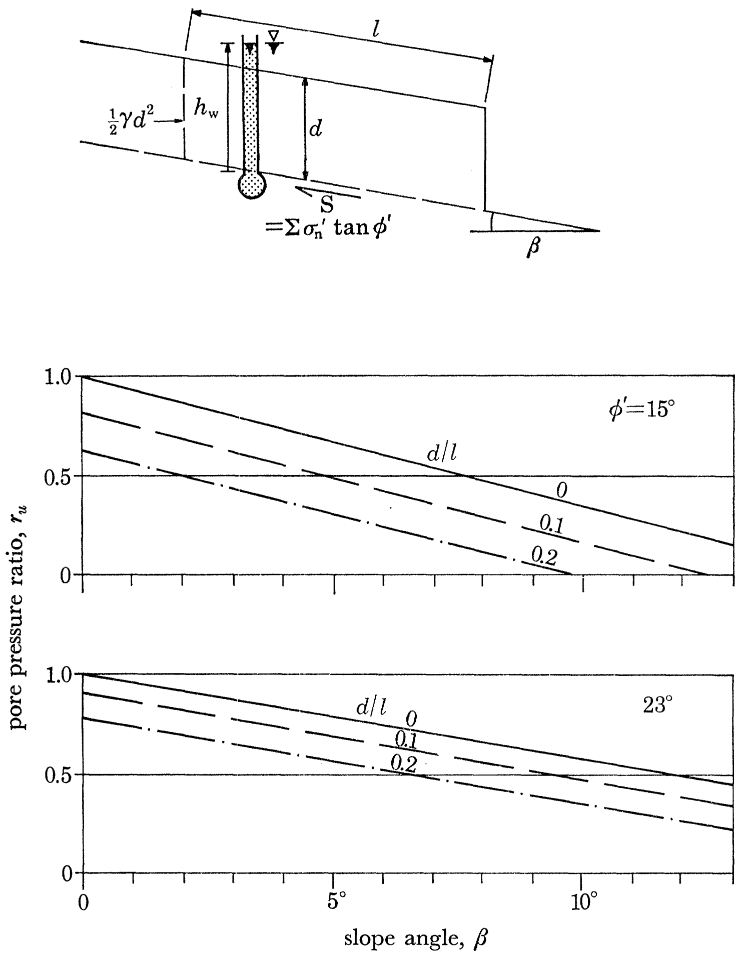

FIGURE A 4. The stability of an inclined layer of frozen ground.

$$r_u = \frac{h_w \gamma_w}{d\gamma} = \cos^2\beta - \frac{\cos\beta \sin\beta}{\tan\phi'} - \frac{d}{2l\tan\phi}$$

The rate and extent of down slope movement would have depended on the times during which excess pore pressures would have developed, on the rate of toe erosion, on the creep rate of the frozen ground and on the rate of accumulation of ice within it.

The influence of these effects on the final valley shape may be envisaged as follows. Ground freezing would result in expansion of the material in the valley slopes, with creep within and shear below the frozen ground resulting in valleyward displacements decreasing with depth and increasing towards the valley centre. No major shear discontinuities would necessarily develop, and any which did would tend to be horizontal and so not disrupt the original stratigraphy. During thawing, fragments of the various strata would be dumped in a loose state beneath and on top of the still frozen ground, arranged according to the original stratigraphy but thinned by an amount depending on the horizontal strain which had occurred during freezing. Consolidation of the dumped material under its own weight would then occur, together with local swelling of clay lumps into voids. Such a process could well result in the structure of the brecciated clay which is currently observed (Chandler 1972). It could also lead to an eventual state of effective stress in the ground varying from the normally consolidated condition to isotropic stress, depending on whether consolidation or swelling was dominant. Erosion of the superficial loose material would be inhibited by overlying blocky material from the harder strata.

The current state of stress in the Upper Lias clay in the slope at a point 6 m below the top of the clay and 200 m from the toe of the slope was examined by Maguire (1975). The horizontal stresses were found to be approximately equal to the vertical stress. This might be the end product of the consolidation process described above. However, it also approximates to the state which would result from stress relief, as predicted on figure A 2.

If the effects of stress relief occurred before ground freezing, then the relatively small movements might have created open fissures where the clay was cemented and have made it more susceptible to ground freezing. Movements due to ground freezing would reactivate a passive bulge and a base shear plane originally formed by stress relief, and the bulge zone would then be enlarged. The presence of well defined and apparently undisturbed shear zones within the brecciated bulge suggests either that the bulge zone was unfrozen at the time of major movements and has remained so since, but had previously been frozen, or that the clay now in the bulge had been frozen under the valley slopes and thawed as it was thrust into the bulge. Thawed ground beneath the centre of a valley can be a feature of permafrost conditions (McRoberts & Morgenstern 1974).

4. Recent slope movements

If the preceding arguments are correct, then major slope movements of the type which formed the Empingham slope should have ceased when periglacial conditions ended. High horizontal stresses would have been unlikely to survive in the brecciated zone, and a substantial factor of safety against further movements due to stress relief is likely to have existed. The calculations presented previously indicate that the two situations may arise in which post-glacial slope movements similar to those induced by periglacial conditions may occur. Firstly, if erosion is sufficient to largely remove the brecciated material, further movements due to stress relief may occur and these will cause fresh bulge movements of small magnitude. Secondly, slope failures may occur due to local oversteepening of the slope, particularly at the toe. Such failures may take the form of relatively shallow slips. However, because of the existence of shear surfaces at residual strength, both at depth and in the previously formed bulge zone, an unusually deep slip may occur, with movements along the base shear and through the bulge, and with inclined shear surfaces of the 'graben' type failing at peak strength and forming in the slope. Such a slip will reactivate the valley bulge. The deformation of the Roman well at Empingham, reported by Horswill & Horton, could be due to a movement of this type.

5. Conclusion

The detailed exploration of the Empingham slope has allowed the strains and displacements which occurred during its formation to be estimated. Vertical and horizontal strains approaching unity and horizontal displacements approaching 200 m have been deduced. Simple analyses of three possible causative mechanisms lead to the following conclusions.

Differential vertical ice loading, although it can clearly cause structures of the valley bulge type, is an unlikely cause of the Empingham movements. The pressures required would be large, and, more particularly, thinning of the strata would be adjacent to the bulge and involve diagonal shears, whereas the slope section shows thinning extending well away from the bulge and no evidence of diagonal shears. Stress relief due to valley formation in a clay in which horizontal stresses are initially high is shown to be capable of producing a base shear and a valley bulge of the type observed at Empingham, but the predicted movements are much smaller than those which are estimated to have occurred. In particular, only a very slight and local thinning and cambering of the strata is predicted. Ground freezing, superimposed on the effects of stress relief, is found to be a possible cause of the thinning and cambering of the valley sides and of the size of the valley bulge movement, which is not accounted for by the effects of stress relief. If this is accepted as the main cause of slope movement, it follows that the major part of the cambering and bulging occurred concurrently with ground freezing.

Superficial slope movements could be caused by a wide variety of loading mechanisms. While simple calculation indicates that ground freezing is the most likely cause of the Empingham movements, analysis of other valley sections containing what appear to be similar structures might show that other loading mechanisms are the most likely cause of the movements in these cases.

References (Vaughan)

Bishop, A. W., Webb, D. L. & Lewin, P. I. 1965 Undisturbed samples of London Clay from the Ashford Common Shaft: strength–effective stress relationships. *Géotechnique* **15**, 1–31.

Brooker, E. W. & Ireland, H. O. 1965 Earth pressures at rest related to stress history. *Can. Geotech. J.* **2**, 1–15.

Chandler, R. J. 1972 Lias clay: weathering processes and their effect on shear strength. *Géotechnique* **22**, 403–432.

Dunlop, P. & Duncan, J. M. 1970 Development of failure around excavated slopes. *J. Soil Mech. Fdns Div. Am. Soc. civ. Engrs* **96**, 471–493.

Maguire, W. M. 1975 Undrained strength and stress–strain behaviour of the brecciated Upper Lias clay. Ph.D. Thesis, University of London.

Mandel, J. & Salencon, J. 1972 Force portante d'un sol sur une assise rigide (etude théorique). *Géotechnique* **22**, 79–93.

McRoberts, E. C. & Morgenstern, N. R. 1974 Stability of slopes in frozen soil, MacKenzie Valley, N.W.T. *Can. Geotech. J.* **11**, 554–573.

Skempton, A. W. 1961 Horizontal stresses in an overconsolidated Eocene clay. *Proc. 5th Int. Conf. Soil Mech. & Fdn Eng.* **1**, 351–357.

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Discussion

A. D. M. Penman (*Building Research Establishment, Garston, Watford, Herts WD2 7JR*)

Dr A. D. M. Penman referred to some evidence of cambering in the Maidstone area observed during an investigation of damage to buildings. The Medway has cut through the Hythe Beds and some way into the underlying clays. The resulting cambering has caused tension cracks or 'gulls' in the Hythe Beds. In general these gulls have filled with loam and show up as loam 'squats' in quarries working the ragstone. Figure 1, plate 1, shows a quarry face parallel to the river; figure 2, plate 1, shows a quarry face at right angles to the river. In the old hand-worked quarries, the loam squats were left and the parallel mounds of loam (figure 3, plate 2) give evidence of the cracks. These form a valuable record of direction and spacing.

The gulls can be something of a nuisance to the engineer, particularly when the loose loam is washed out by concentrations of water from leaking pipes or soakaways, causing swallow holes at ground surface. The old builder got over these difficulties by spanning across the cracks with arched foundations. Unfortunately, modern buildings with shallower foundations are often damaged when these swallow holes appear.

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1

2

FIGURES 1 AND 2

(*Facing p.* 462)

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

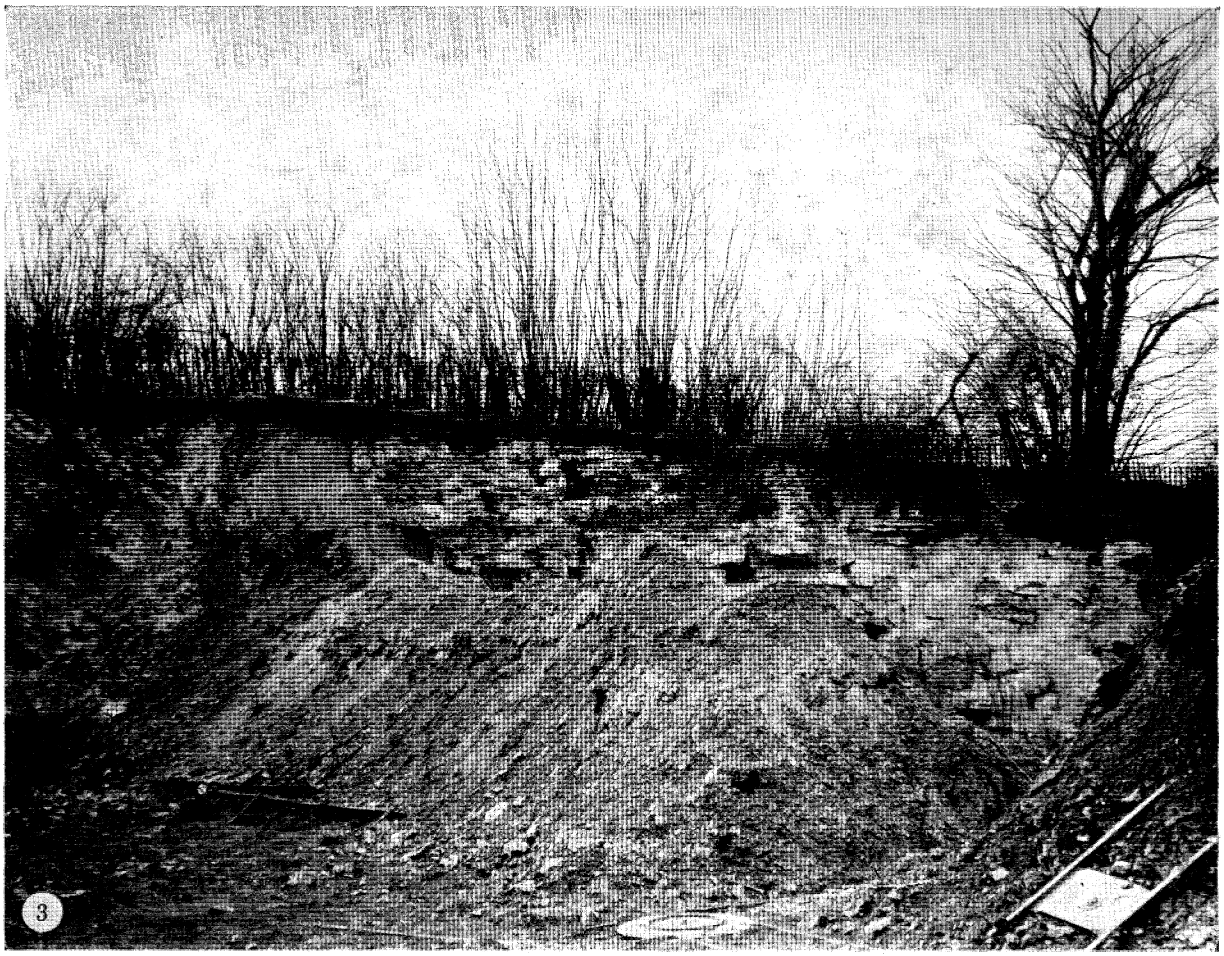


FIGURE 3

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

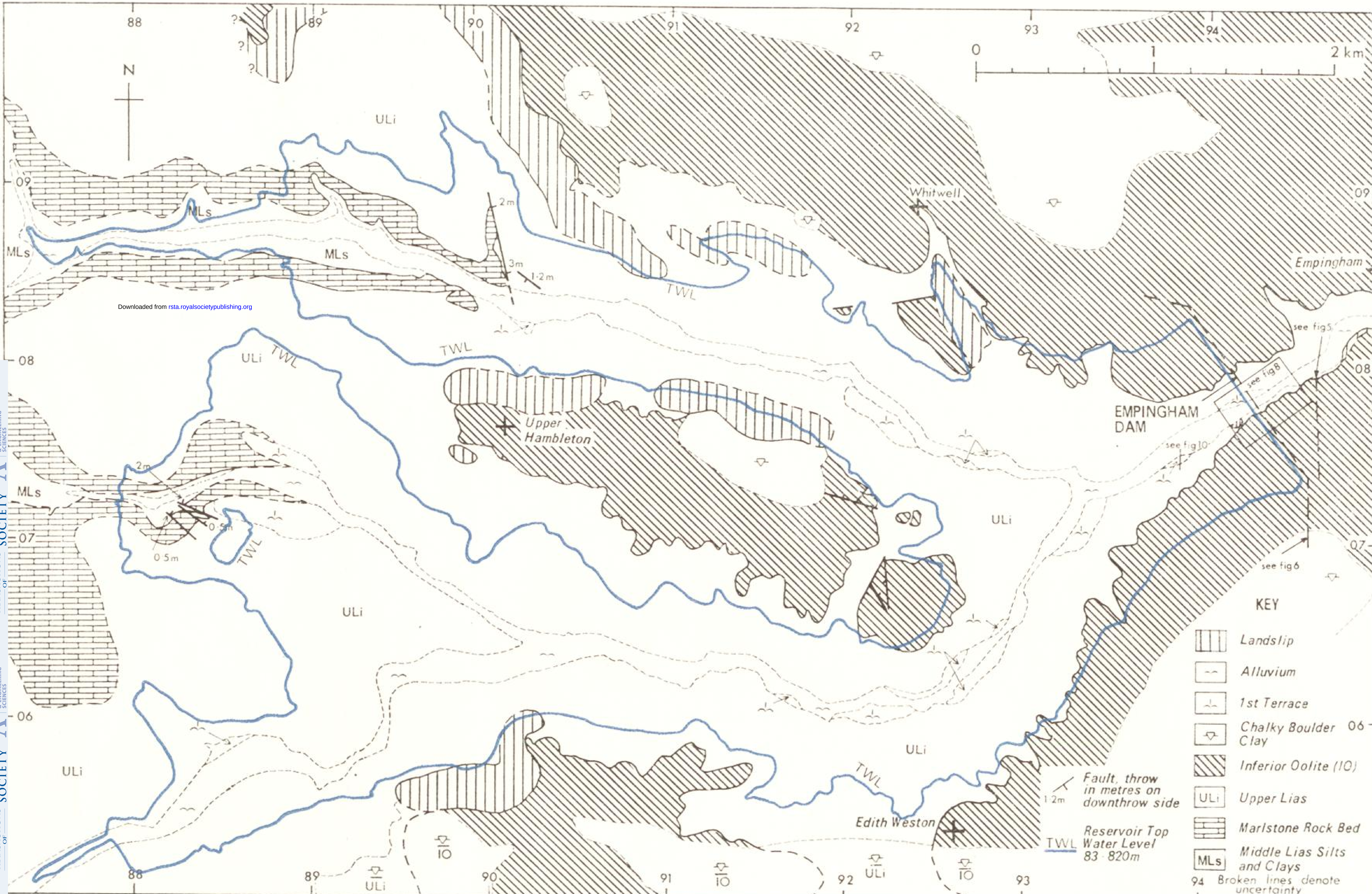


FIGURE 1. Geological sketch map of the Empingham Reservoir site.

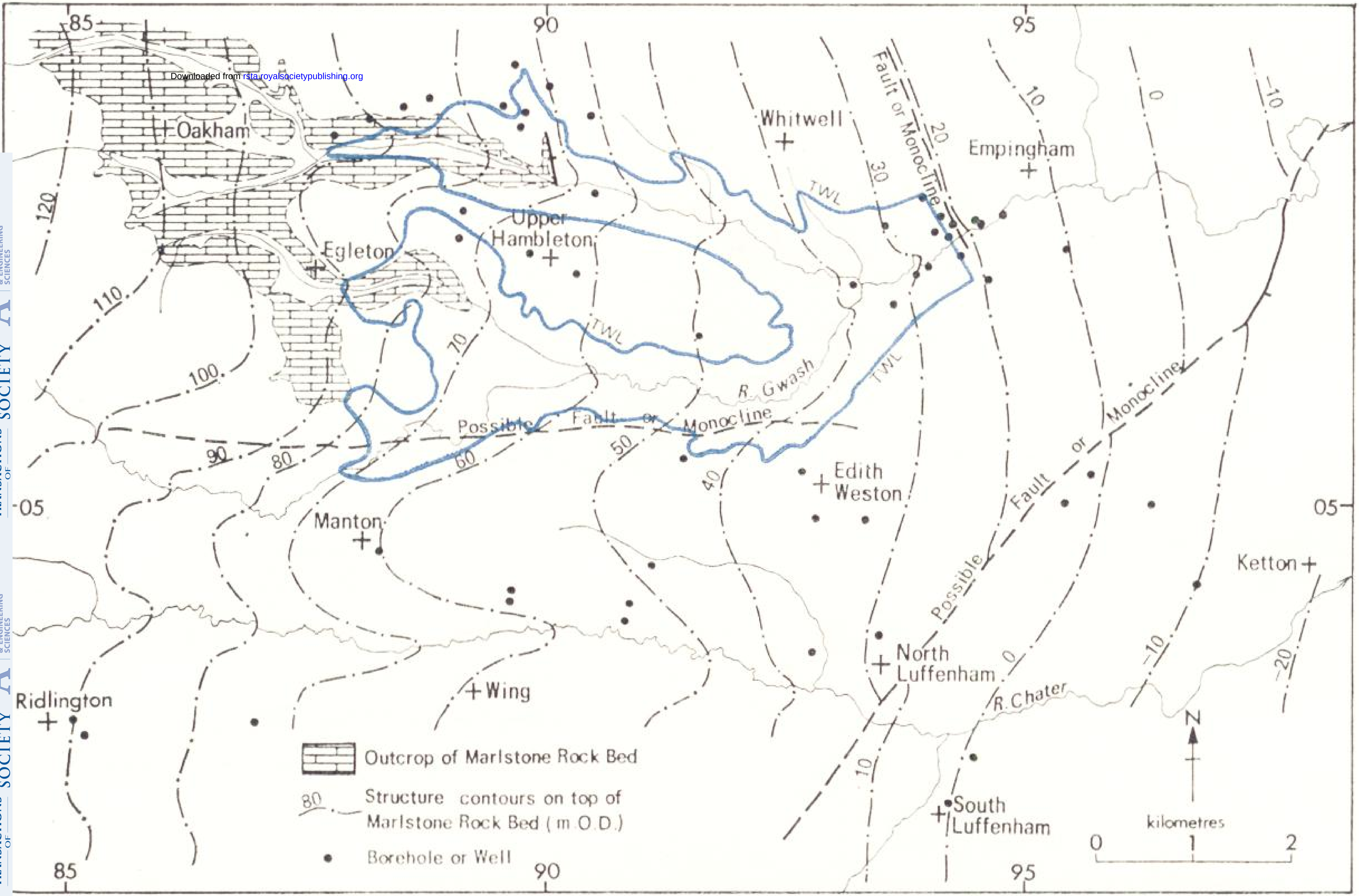
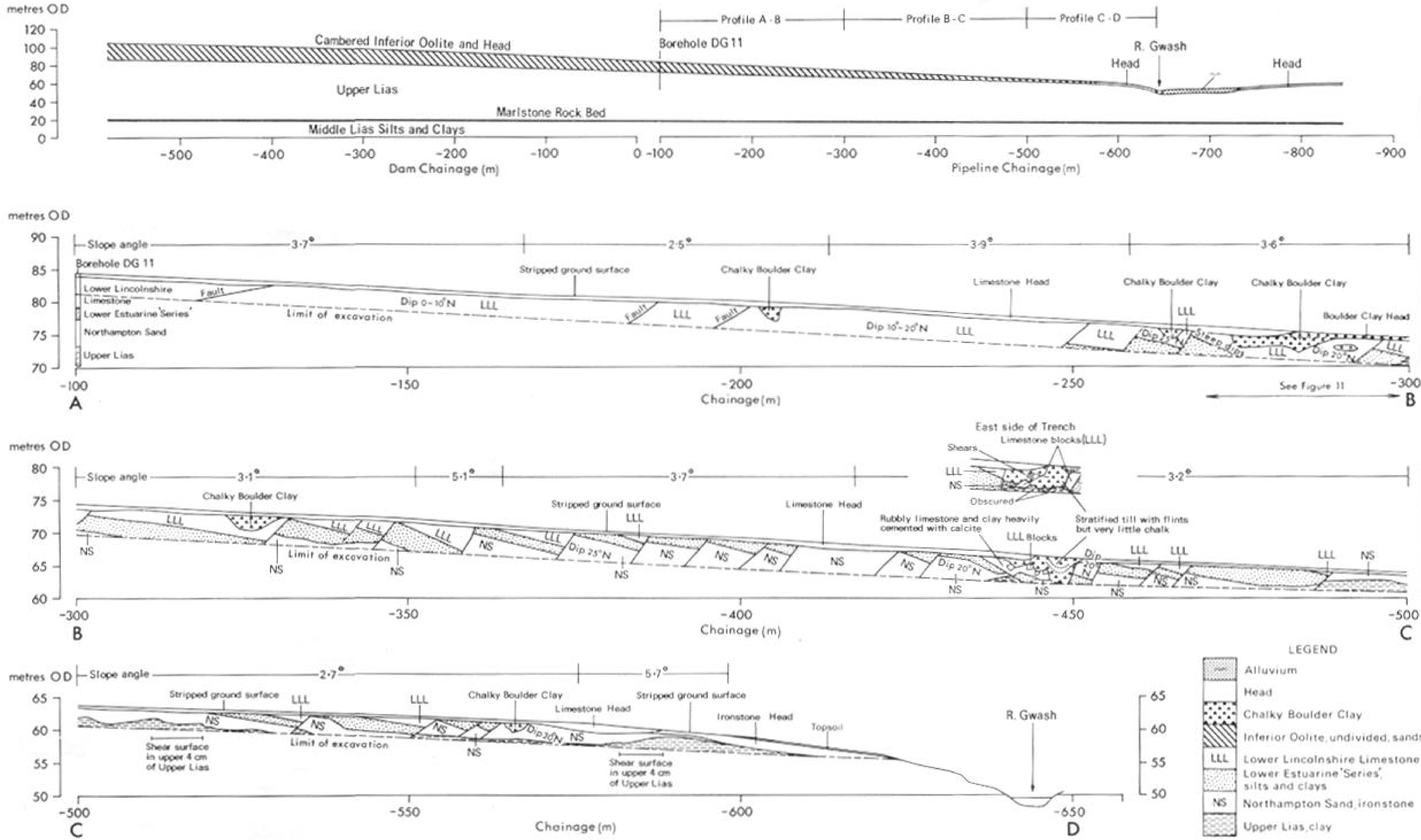
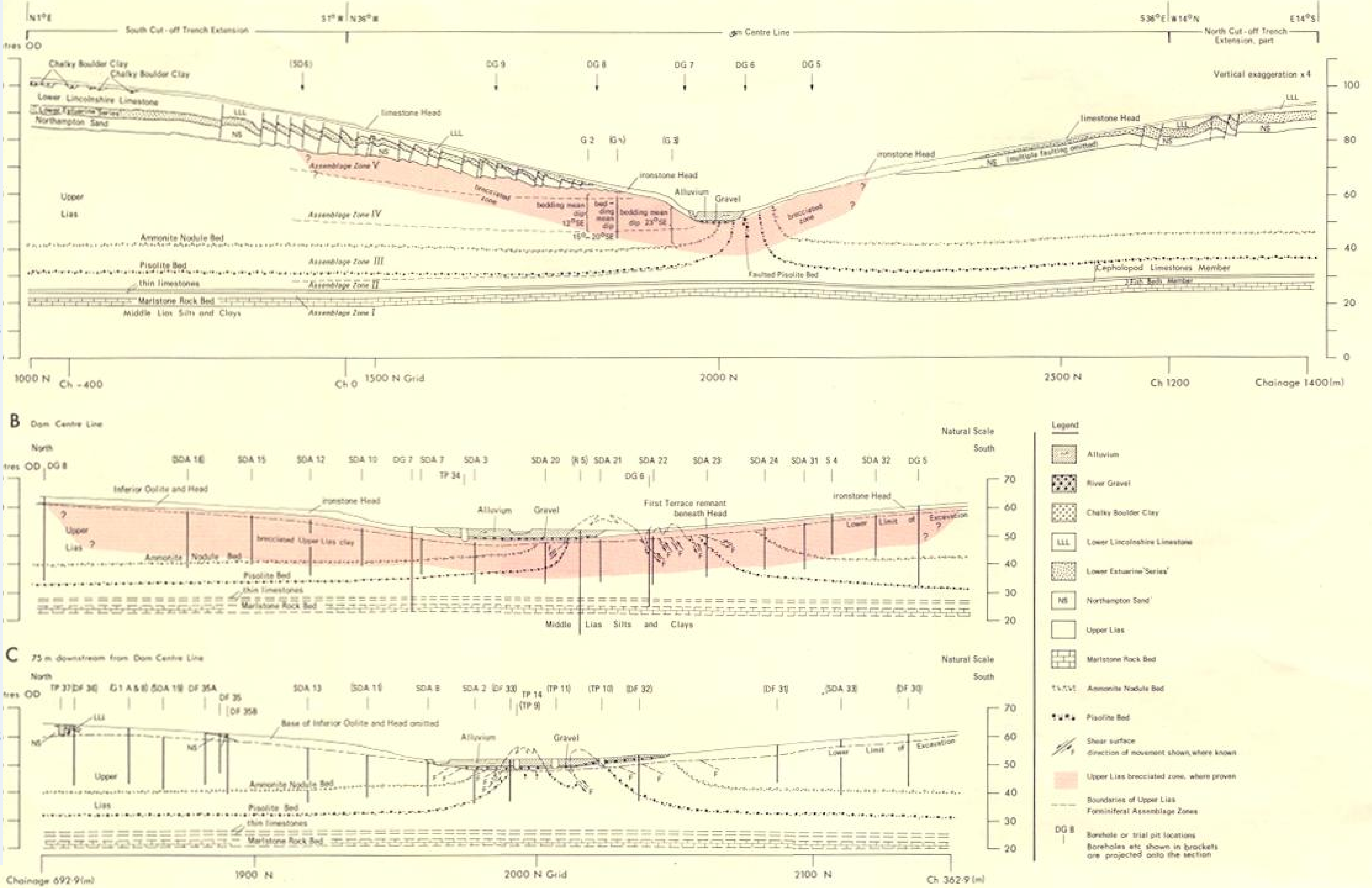


FIGURE 3. Contours on the top of the Marlstone Rock Bed in the vicinity of the Empingham Reservoir site.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

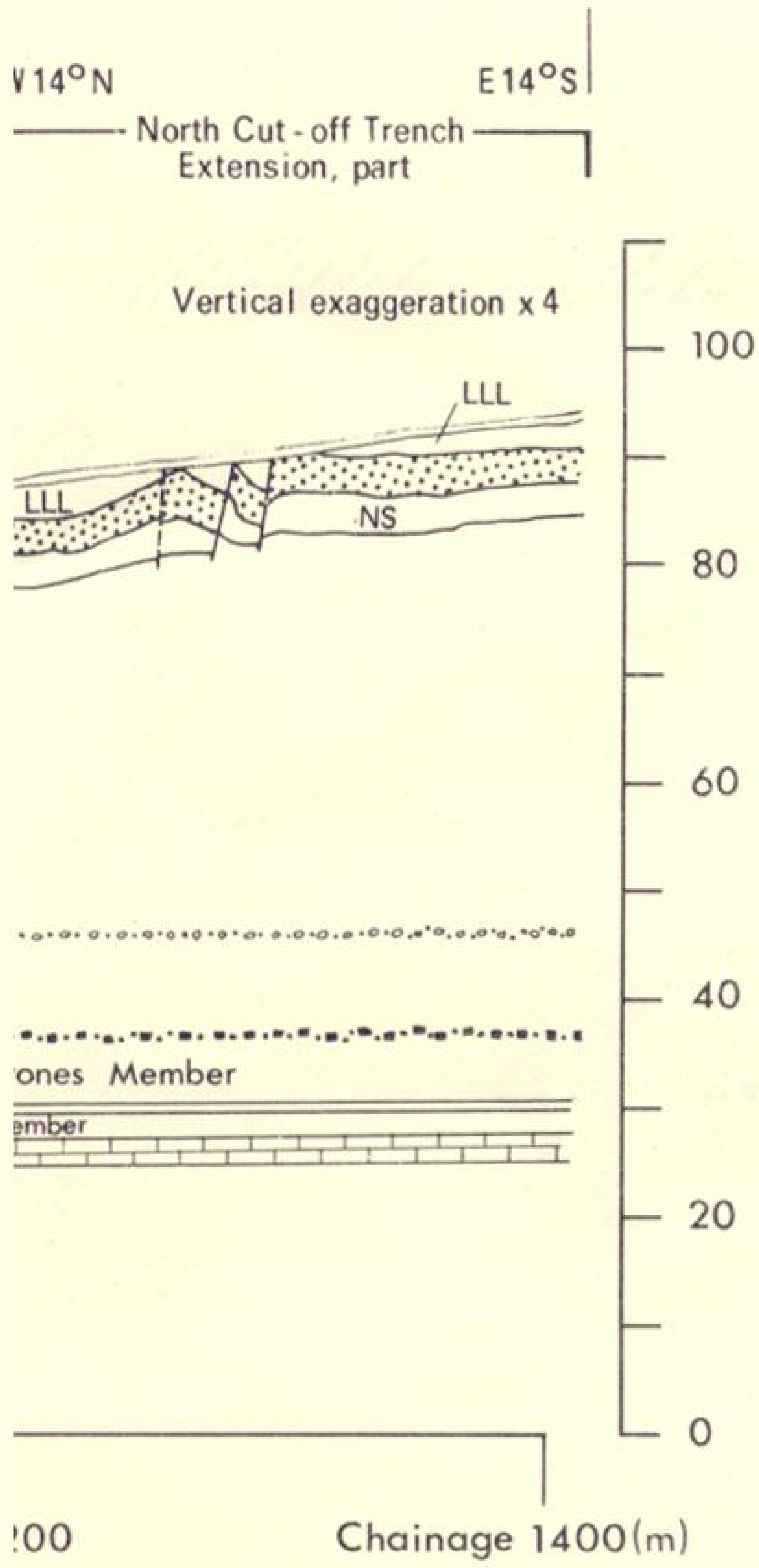


metres OD
Profile A-B
Profile B-C
Profile C-D
Cambered Inferior Oolite and Head
Borehole DG 11
R. Gwash
Head
Head
Upper Lias
Marlstone Rock Bed
Middle Lias Silts and Clays
Dam Chainage (m)
Pipeline Chainage (m)
Slope angle
3·7°
2·5°
3·9°
3·6°
Borehole DG 11
Lower Lincolnshire Limestone
Lower Estuarine 'Series'
Northampton Sand
Upper Lias
Fault
Stripped ground surface
Chalky Boulder Clay
Limit of excavation
Dip 0-10°N
Dip 10°-20°N
Limestone Head
Boulder Clay Head
Steep dip
See Figure 11
Chainage (m)
A
B
3·1°
5·1°
3·7°
3·2°
East side of Trench
Limestone blocks (LLL)
Shears
Obscured
Rubbly limestone and clay heavily cemented with calcite
LLL Blocks
Stratified till with flints but very little chalk
Dip 25°N
Dip 20°N
C
2·7°
5·7°
Shear surface in upper 4 cm of Upper Lias
Ironstone Head
Topsoil
D
LEGEND
Alluvium
Head
Chalky Boulder Clay
Inferior Oolite, undivided, sands
Lower Lincolnshire Limestone
Lower Estuarine 'Series', silts and clays
Northampton Sand, ironstone
Upper Lias, clay


South Cut-off Trench Extension
Centre Line
North Cut-off Trench Extension, part
Vertical exaggeration x 4
Chalky Boulder Clay
Lower Lincolnshire Limestone
Lower Estuarine Series
Northampton Sand
limestone Head
ironstone Head
Assemblage Zone V
Assemblage Zone IV
Assemblage Zone III
Assemblage Zone II
Assemblage Zone I
brecciated zone
Alluvium
Gravel
Upper Lias
Ammonite Nodule Bed
Pisolite Bed
thin limestones
Marlstone Rock Bed
Middle Lias Silts and Clays
Faulted Pisolite Bed
Cephalopod Limestones Member
(multiple faulting omitted)
1000 N
Ch -400
Ch 0
1500 N Grid
2000 N
2500 N
Ch 1200
Chainage 1400(m)
B Dam Centre Line
Natural Scale
North
South
Inferior Oolite and Head
brecciated Upper Lias clay
First Terrace remnant beneath Head
Lower Limit of Excavation
C 75 m downstream from Dam Centre Line
Base of Inferior Oolite and Head omitted
Chainage 692·9(m)
1900 N
2000 N Grid
2100 N
Ch 362·9 (m)
Legend
Alluvium
River Gravel
Chalky Boulder Clay
Lower Lincolnshire Limestone
Lower Estuarine 'Series'
Northampton Sand
Upper Lias
Marlstone Rock Bed
Ammonite Nodule Bed
Pisolite Bed
Shear surface direction of movement shown, where known
Upper Lias brecciated zone, where proven
Boundaries of Upper Lias Foraminiferal Assemblage Zones
Borehole or trial pit locations
Boreholes etc shown in brackets are projected onto the section

N 1° E
S 1° W
N 36° W
South Cut-off Trench Extension
metres OD
Chalky Boulder Clay
Chalky Boulder Clay
(SD6)
DG 9
DG 8
Lower Lincolnshire Limestone
Lower Estuarine Series
Northampton Sand
LLL
NS
limestone Head
LLL
NS
G 2
Assemblage Zone V
brecciated zone
bedding mean dip 12°SE
bed-ding mean dip 15°–20°SE
Upper Lias
Assemblage Zone IV
Ammonite Nodule Bed
Assemblage Zone III
Pisolite Bed
thin limestones
Assemblage Zone II
Marlstone Rock Bed
Middle Lias Silts and Clays
Assemblage Zone I
1000 N
Ch −400
Ch 0
1500 N Grid
B Dam Centre Line
North
metres OD
DG 8
(SDA 18)
SDA 15
SDA 12
SDA 10
DG 7
SDA 7
SDA 3
TP 34
SDA 20
(R 5)
SDA 2
Inferior Oolite and Head
ironstone Head
Alluvium
Gravel
Upper Lias
brecciated Upper Lias clay
Ammonite Nodule Bed
Pisolite Bed
thin limestones
Marlstone Rock Bed
Middle Lias
C 75 m downstream from Dam Centre Line
North
metres OD
TP 37
(DF 36)
(G 1 A & B)
(SDA 19)
DF 35A
DF 35
DF 35B
SDA 13
(SDA 11)
SDA 8
SDA 2
(DF 33)
TP 14
(TP 9)
(TP 11)
(TP 10)
LLL
NS
NS
Base of Inferior Oolite and Head omitted
Alluvium
Gravel
Upper
Lias
Ammonite Nodule Bed
Pisolite Bed
thin limestones
Marlstone Rock Bed
Chainage 692·9(m)
1900 N
2000 N Grid


S 36° E
W 14° N
Dam Centre Line
DG 8
DG 7
DG 6
DG 5
G 2
(G 4)
(G 3)
limestone Head
LLL
NS
NS (multiple faulting omitted)
ironstone Head
ironstone Head
Alluvium
Gravel
bed-ding mean dip
bedding mean dip 23°SE
15°–20°SE
brecciated zone
?
Faulted Pisolite Bed
Cephalopod Limestones Memb
Fish Beds Member
2000 N
2500 N
Ch 1200
Natural Scale
South
SDA 21
SDA 22
DG 6
SDA 23
SDA 24
SDA 31
S 4
SDA 32
DG 5
First Terrace remnant beneath Head
ironstone Head
Lower Limit of Excavation
F
70
60
50
40
30
20
Lias Silts and Clays
Natural Scale
South
(TP 10)
(DF 32)
(DF 31)
(SDA 33)
(DF 30)
Lower Limit of Excavation
F
70
60
50
40
30
20
2100 N
Ch 362·9 (m)
Legend
Alluvium
River Gravel
Chalky Boulder Clay
LLL
Lower Lincolnshire Limestone
Lower Estuarine 'Series'
NS
Northampton Sand
Upper Lias
Marlstone Rock Bed
Ammonite Nodule Bed
Pisolite Bed
Shear surface
direction of movement shown, where kn
Upper Lias brecciated zone, where pro
Boundaries of Upper Lias
Forminiferal Assemblage Zones
DG 8
Borehole or trial pit locations
Boreholes etc shown in brackets are projected onto the section



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PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

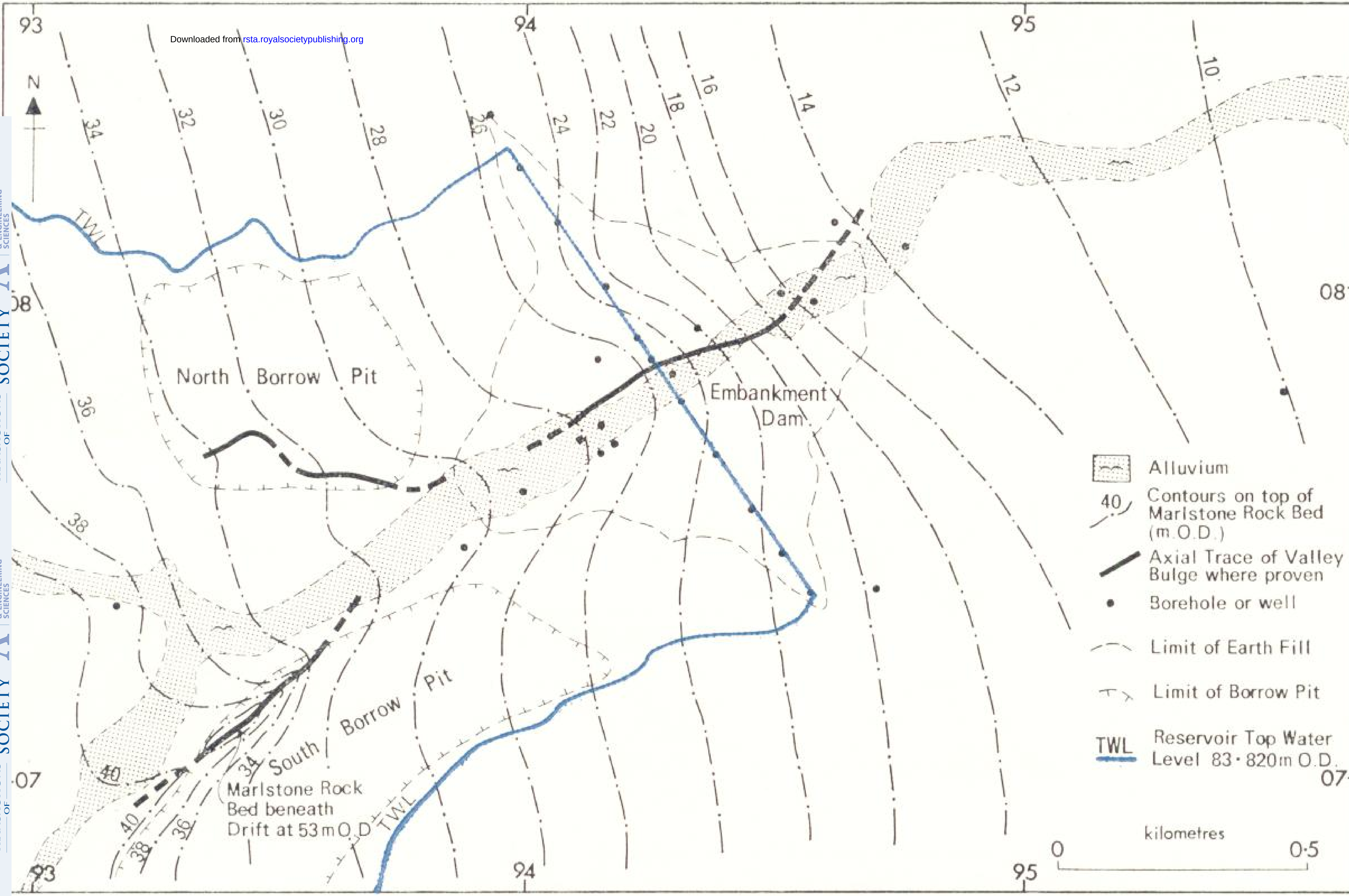

FIGURE 7. Location of valley bulge structures near the Empingham Dam site.

FIGURE 8. Generalized map showing the structure of the Upper Lias in the valley bulge at the Empingham Dam site.

FIGURES 1 AND 2

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Figure 3