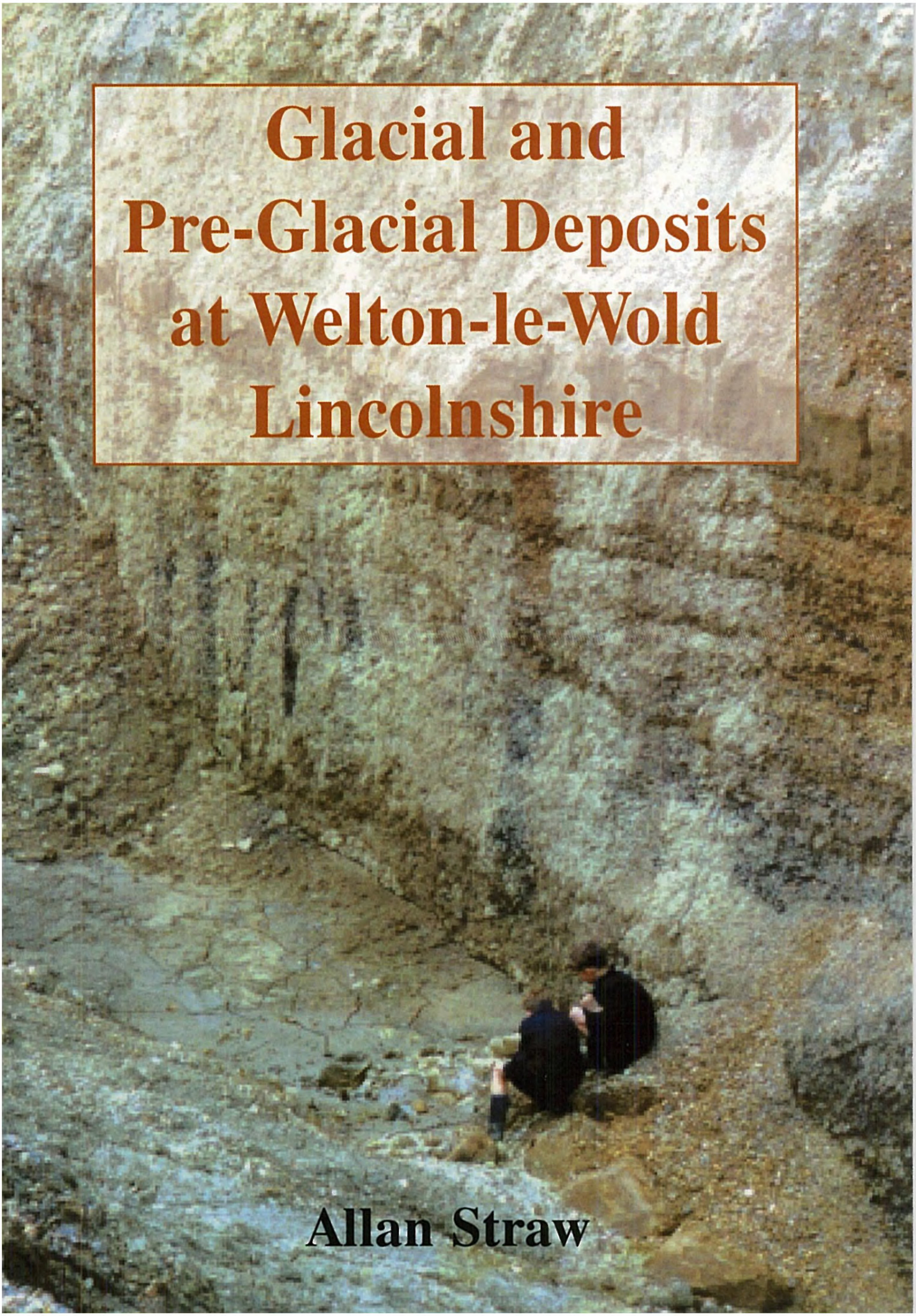
Glacial and Pre-Glacial Deposits at Welton-le-Wold Lincolnshire



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INTRODUCTION

The first formal descriptions of sediments laid down at Welton-le-Wold within the Quaternary (the last two million years or so of geological time) are probably those in the Memoir of the Geological Survey of East Lincolnshire (1887) by A.J. Jukes-Browne. He recorded an exposure in the south part of the subsequently-quarried western area (about TF 281879) as:

	Feet
4. Brown clayey soil	1–3
3. Stiff brown boulder clay of Hessle type	10
2. Hard stony clay, passing down into an unstratified mixture of clay and stones	4
1. Roughly stratified flint gravel	12

Another section, some 300 m northeast, in what became the east quarry (about TF 283881) was also detailed:

	Feet
Soil, loamy clay	1
Reddish-brown clay of Hessle type, containing much chalk and some large flints	7
Hard yellow-brown sandy clay, with a ferruginous layer near the base containing brown-coated flints	$1^1/_2$
Unstratified rubble of small angular flints in a matrix of hard sandy clay	6
Roughly stratified flint gravel in a sandy matrix	16
Similar gravel with contorted bedding	10

The pits had been opened to obtain gravel for roadways and sand for building purposes from under some 3 to 5 m of overburden, but it was not perhaps until the second quarter of the twentieth century that commercial quarrying was carried out on a large scale, and then particularly with wartime demand for aggregate in the 1940s. The earlier pits were subsumed in expanded excavations east and west of the minor road that runs north to south through the site (Figure 1).

The writer first visited the quarry in November 1954 in the early stages of fieldwork which formed the basis for a doctoral thesis on the geomorphology of the Lincolnshire Wolds (Straw, 1964). Irregularly-spaced visits continued until 1973, when the quarry reached the end of its working life, and occasional ones since.

The descriptions and discussions which follow rest, therefore, on direct observations made over almost 20 years and reported, in part, in publication (Alabaster and Straw, 1976; Straw, 1969, 1976), supported by a modest photographic record, and on much subsequent consideration of environmental circumstances and chronology within the context of Quaternary events in eastern England as a whole (Straw, 1979a,b, 1982, 1991).

By 1954, approximately half of the final quarried area had been worked out, and sections were exposed both east and west of the road, revealing between 4 and 7 m of overburden on a similar thickness of flinty gravels. Excavation progressed northward on a strip system mainly, in the later years, to obtain the flint-rich upper 5 to 8 m of the gravel deposits. East of the road sections were aligned broadly southeast to northwest. Westward they lay approximately east to west but turned toward the southwest near the west end. Operations required the removal of a 6 to 10 m-wide strip of overburden, before 'drag-line' lifting of the underlying sands and gravels. The overburden was dumped alongside in the trench left by excavation of the previous strip (Plates 2, 5). Consisting of various periglacial and glacial materials described below, it thickened northward across the west quarry from 3 to 4 m in the south, to 13 to 15 m along the northern limit of the workings (Figure 2). Because its basal contact with the underlying sands and gravels was essentially horizontal, the thickening was a consequence of the southward slope of the ground surface. This surface lay at about 80 m OD in the southern quarry area rising to the west–east spur above the quarry. This high ground declines east from about 115 m OD to 95 m OD, except where transected by the small valley occupied by the road (Plate 2).

On their southern edge, the Quaternary deposits were cut across by the modern Welton valley and originally presented bluffs maintained by basal springs and seepage (Figure 1). The valley commences just over a mile west of the village church and lies wholly within Chalk of the Welton and flint-free Ferriby Formations (British Geological Survey, 1999). Below the village the southerly slopes remain on Chalk as far east as the entrance to the Welton Vale gorge, but the northerly slopes are broken by a tributary from the northwest developed along the western border of the Quaternary deposits. With its floor at about 74 to 70 m OD through the village, considerable deepening of the Welton valley has occurred since these materials were emplaced. At and above the village it is tempting to confine this erosion phase within prominent breaks-of-slope on the Chalk visible at about 90 m OD, and regard upper gentler valley-sides as representing the form of the Welton valley when broadly accordant with the original surface on the quarry overburden. If the upper Welton valley did exist during the accumulation of the Quaternary deposits then materials from within its catchment could have contributed to them. At present the catchment above the quarry area covers some 1.12 ml^2 (2.98 km^2) and includes areas of gently-inclined interfluve surface (Figure 1).

The field disposition of the Quaternary deposits shows them to lie within a wide depression some 600 m across from northeast to southwest. For reasons explained below it may be part of a pre-existing or palaeo-valley that drained generally eastward from higher parts of the Wolds around Kelstern and Ludford, and to which the present Welton valley would have been tributary. The floor of this old valley at the quarry (doubling also as the base of the Quaternary deposits) must be developed on Chalk of the Ferriby Formation, and lies at c.65 to 70 m OD. This floor was never seen by the writer, but quarry workers described the lowest metre or two of the deposits as chalky and earthy gravels. The consistent thickness of the gravel deposits across the whole of the quarry area indicates a generally level floor, presumably stream-eroded.

The down-valley gradient of this Chalk floor could not be determined within the quarry area, but it is possible to make two tentative assessments.

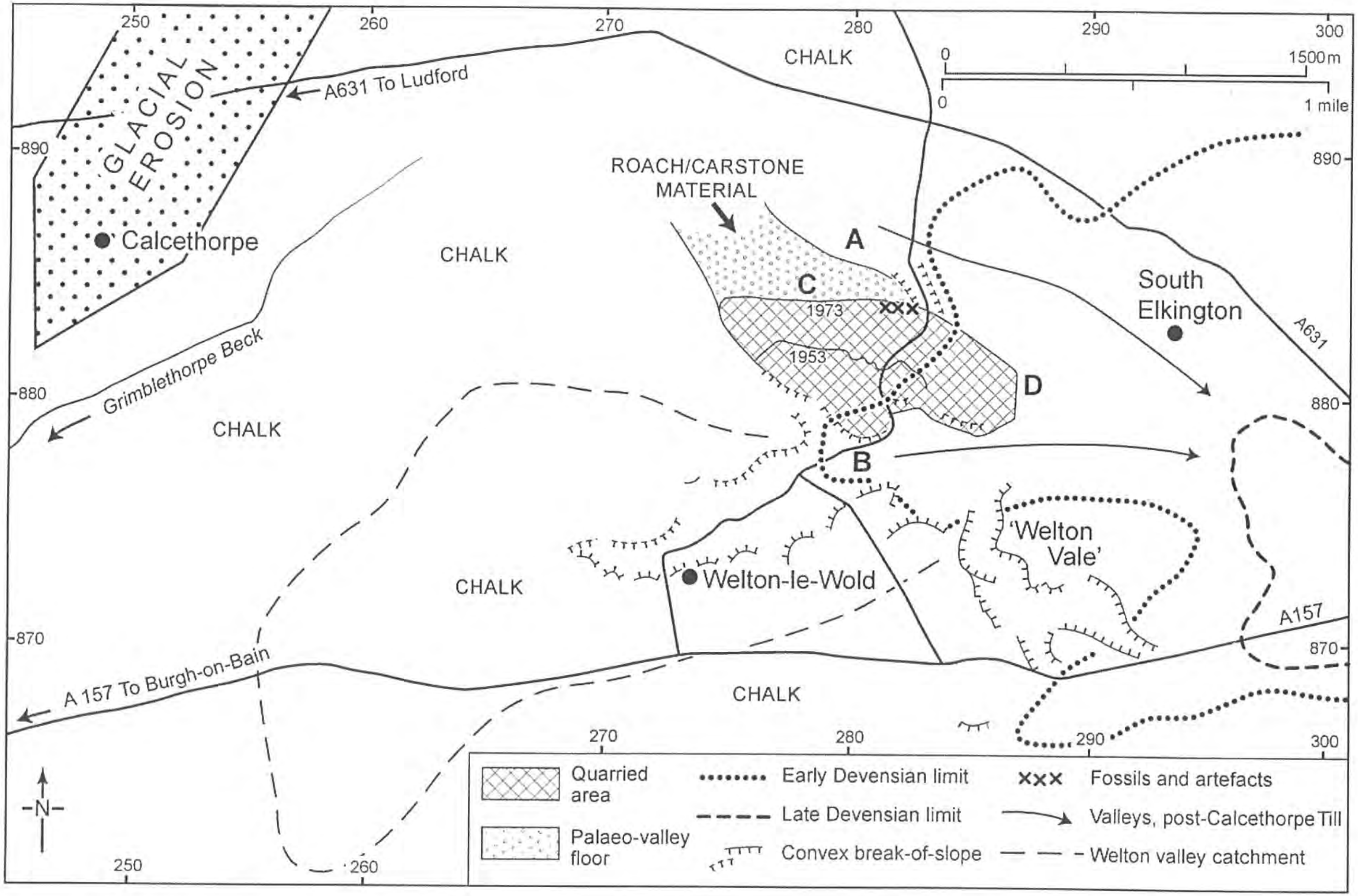
250
260
270
280
290
300
0
1500m
0
1 mile
890
880
870
GLACIAL EROSION
Calcethorpe
A631 To Ludford
CHALK
ROACH/CARSTONE MATERIAL
A
C
1973
1953
D
B
South Elkington
A631
Grimblethorpe Beck
CHALK
CHALK
Welton-le-Wold
'Welton Vale'
A157
A 157 To Burgh-on-Bain
CHALK
N
Quarried area
Palaeo-valley floor
Early Devensian limit
Late Devensian limit
Convex break-of-slope
Fossils and artefacts
Valleys, post-Calcethorpe Till
Welton valley catchment

Figure 1

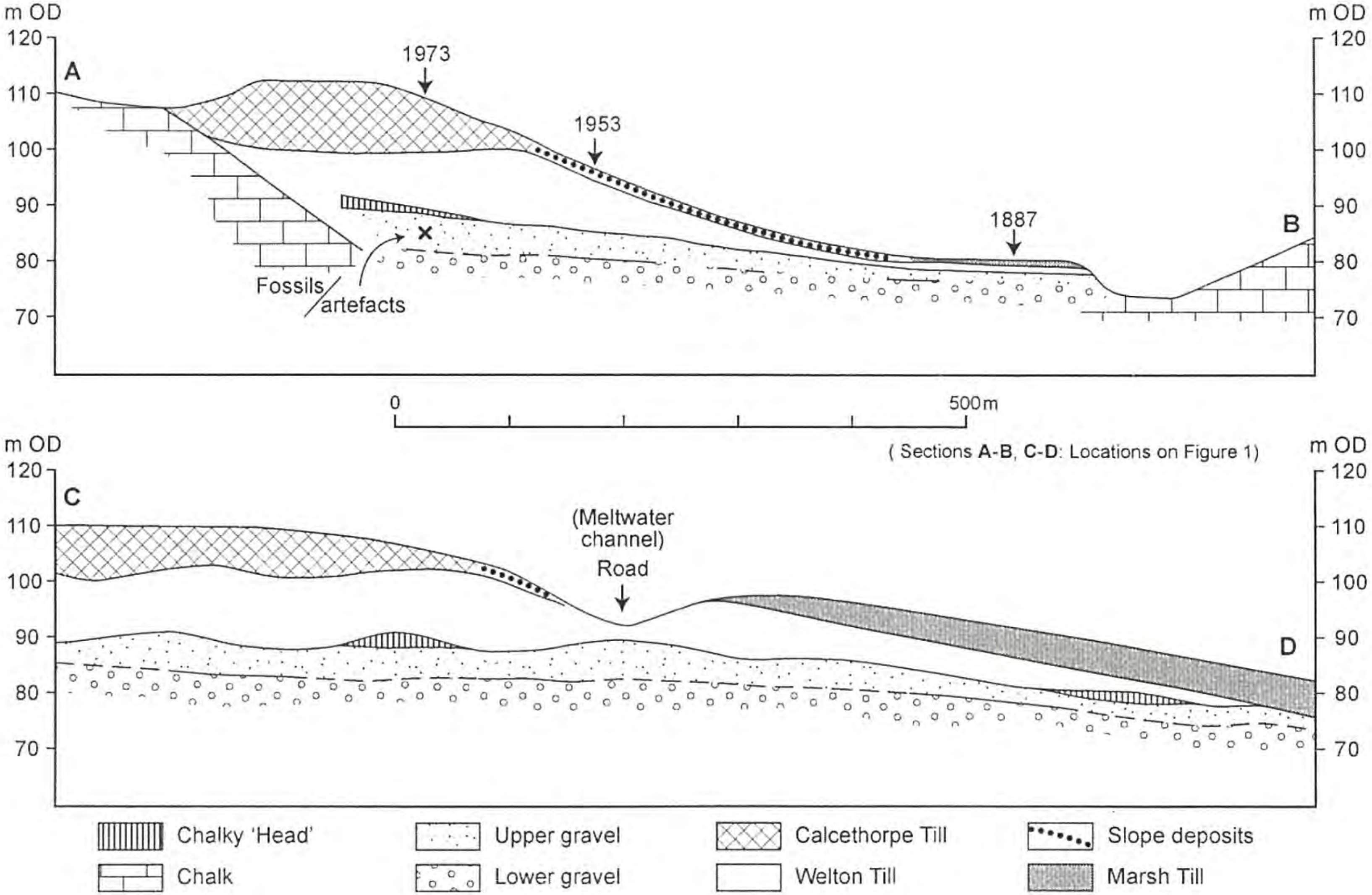
m OD
120
110
100
90
80
70
A
B
1973
1953
1887
Fossils/artefacts
×
0
500m
(Sections A-B, C-D: Locations on Figure 1)
C
D
(Meltwater channel)
Road
Chalky 'Head'
Chalk
Upper gravel
Lower gravel
Calcethorpe Till
Welton Till
Slope deposits
Marsh Till

Figure 2

1. Southeast of South Elkington, in higher ground at Cow Pastures (TF 307875) lies a vestigial deposit of flinty gravel at c.70 m OD, long ago worked out, and in composition much like the upper part of the Welton Gravels which lies between c.75 to 82 m OD at the quarry. If it is indeed an outlier then, lying 1.7 miles (2.73 km) from Welton, a gradient of about 1:280 is indicated.
2. It is claimed below that materials from Lower Cretaceous rocks, up-valley to the northwest and west, entered into the Welton deposits. Available outcrops lie around Ludford at c.110 to 115 m OD, 4.4 miles (7 km) distant from Welton. A gradient of the order of 1:200 is indicated. Valley-floor gradients in members of the Lud drainage system today average 1:100.

Such is the setting of the Quaternary deposits at Welton. A full interpretation of the deposits will clearly require consideration of the geomorphology of a wider area than just the quarry.

The stratigraphy and nomenclature of the deposits, confirming and extending the views of Jukes-Browne (1887) have been determined in several publications (Straw, 1961, 1969; Alabaster and Straw, 1976).

West quarry	Slope deposits	*East quarry*	Marsh Till
	Calcethorpe Till		Welton Till
	Welton Till		Welton Gravels:
	Welton Gravels:		Upper Gravel
	Upper Gravel		Lower Gravel
	Lower Gravel		

Referring back to Jukes-Browne's sections, it is now clear that even in the 1880s, the Welton Gravels (roughly stratified), Welton Till (with ferruginous base) and Marsh Till (Hessle) were exposed. Indeed, Jukes-Browne (1887, p. 100) also noted the slope deposits which, he suggested, 'may have been formed from the materials of the Chalky Boulder Clay which caps the hill above'.

It is also obvious that, in a brief account of the Welton deposits written in 1964 and published some years later (Straw, 1969), two misinterpretations were made – first, weathered Welton Till was included in the Marsh Till and second, the underlying flinty gravel was thought to be outwash material mainly because an oolitic limonite component might have been derived from a Lower Cretaceous inlier present to the east beneath Louth and buried by glacial deposits. Later work has revealed the extent of the Welton palaeo-valley, the probability of Lower Cretaceous inliers to the west, and a clear distinction between Marsh and Welton Tills.

In December 2004, the writer provided 43 photographs of the quarry and the sediments taken between 1954 and 1973 to The Collection, Lincolnshire County Council (formerly the City and County Museum, Lincoln) together with explanatory notes, to complement its holdings of the artefacts and fossils discovered at Welton in 1969 to 1973 (Alabaster and Straw, 1976) and also described below.

WELTON GRAVELS – LOWER GRAVEL

This division of the Gravels (Figure 2) rested on the Chalk floor of the quarry, averaged some 5 to 7 m in thickness, and was distinguishable from an Upper Gravel in its lithology and sedimentary structure and by an unconformable relationship (Plate 1).

In 1969 and 1970 when sections were surveyed for publication (Alabaster and Straw, 1976) the Lower Gravel was barely visible because of difficulties of excavation and back-filling, and is not exposed today. Better exposures in previous years permit description.

The deposit, consistent in thickness and altitude across the whole quarry area, revealed an aggradational sequence above the Chalk base. It comprised well- to moderately-sorted planar and lenticular seams of clast-supported gravel, quartz sand, and silt, with the sand grade dominant and notably no chalk component (Plate 1). Individual beds were less than 50 cm thick, some displayed trough cross-bedding, others such as sandy silts were upward fining. Impersistent, thin sand seams penetrated the gravels, and gravels likewise the finer materials.

The overall character was that of undisturbed, braided-stream deposition indicating variable discharge within a multiple-channel system, though no evidence such as large trough forms or coarse material for very high energy flows was seen. However, in two instances in the upper layers of the Gravel, the fluvial sedimentary structures had been disrupted. In 1970 a small V-shaped structure, interpreted as an ice-wedge cast, was seen to penetrate the Lower Gravel for 70 cm below the contact with the Upper Gravel (Plate 3) (Alabaster and Straw, 1976, Plate 7A). In 1957, toward the east end of the section west of the road (TF 28098825) a large and complex subsidence structure was seen to affect the top 3 m of the Lower Gravel (Plate 4). Some 3 m across at the top, it narrowed downward by numerous step-faults until it was 50 cm wide when obscured by talus. A linear feature, it was observed again three months later after the face had been worked back some 5 m. In view of the spaced and irregular visits the writer was able to make, it is very likely that more such features occurred but were destroyed without record.

Flint fragments, angular and sub-angular, and less than 7 cm across, constituted the whole of the gravel fraction. In spite of the proximity of glacial deposits, no exotic material transportable by glaciers has been found in the gravel. The flint ultimately derives from the Chalk but, as a highly durable material, can be accumulated in and subsequently reworked from a variety of sediments including soils, and perhaps on more than one occasion.

The Chalk of much of the higher ground in the putative catchment of the palaeo-valley was the Welton (Middle) Chalk which contains nodular flints and the Burnham (Upper) Chalk with tabular flints. Ferriby (Lower) Chalk is flint-free and lies beneath the quarry and adjacent valley-sides, and would have underlain much of the headward area if that was around Calcethorpe and Ludford (British Geological Survey, 1999). Dominantly erosional processes had obviously produced a considerable valley before deposition of the Lower Gravel commenced. Erosion upstream would have continued during deposition, but the flint fragments are of consistently small size and, surprisingly, there is no Chalk constituent in the Lower Gravel which suggests that there was no direct erosion of Chalk exposures along the valley. It may be, therefore, that the Chalk was being eroded more by solution and carbonation (i.e. chemical rather than mechanical weathering) and that the flints were being derived from soils rather than directly from bedrock, both circumstances pointing to a woodland cover on the slopes.

Sand was the pervasive material, providing much of the matrix of the gravel beds and a substantial constituent of some of the silt layers, as well as forming seams and lenses up to 50 cm thick. Analyses published in 1976 of samples collected in 1970 to 1972 revealed the bulk of the coarse fraction of the sand to consist of rounded and sub-rounded quartz grains. In the medium and fine sand fractions more sub-rounded quartz was observed and an increasing proportion of whole and fractured limonite ooliths. Indeed almost half of the fine sand fraction of some samples consisted of chips and partial shells of ooliths. These two characteristics of the sands, i.e. high proportion of rounded quartz grains and substantial quantities of limonite ooliths, are distinctive and problematical, because neither of the materials could be derived from the Chalk.

However, within the Lincolnshire Wolds limonite ooliths occur profusely in certain members of the marine Lower Cretaceous rocks, particularly in the Claxby Ironstone Formation which along the scarp between Nettleton and Walesby formerly supported a nineteenth century mining industry, and in the stratigraphically higher ferruginous mudstones and limestones of the Roach Formation (Swinnerton and Kent, 1976). The latter crop out today in the scarps of the southern Wolds but also as inliers in the headward parts of several Wold dipslope valleys such as Oxcombe and Thoresway. Roach iron-rich beds are known to extend, perhaps as a facies of the Upper Tealby Clay, as far north as Nettleton and the several heads of the River Bain. For oolitic limonite to be present in large quantities in the Lower Gravel at Welton exposures of Roach beds must have been available upstream, and it is on this premise that the head of the palaeo-Welton valley can be projected generally westward into the Kelstern–Ludford area presently covered by extensive glacial deposits. A gradient of about 1:200 would have been available from Roach outcrops to Welton. The many signs of abrasion and fracture of ooliths in the Gravels confirms their transport and derivative nature.

Such a connection between the Kelstern–Ludford area and Welton is supported by the occurrence of the rounded quartz grains. They, too, could not originate in the Chalk, nor from glacial sources. Rather it is the Carstone of the western Wolds, stratigraphically higher than the Roach beds and therefore equally accessible in inliers and along the scarp, that is the likely source. The Carstone is composed largely of quartz grains well rounded in a marine environment. Like the ooliths, therefore, Carstone sands could have been carried down the palaeo-valley to Welton and beyond, and the roundness of the quartz grains in the Welton sands must be regarded as an inherited characteristic, rather than the result of abrasion during a relatively short distance of transport.

Silt-grade material constituted no more than 10 to 15% of the sand beds and considerably less in the matrix of the gravels. Sporadic planar and lenticular seams of sandy silt up to 15 cm thick were, however, interbedded with the sands and gravels. In these, 1976 analyses showed the silt component to be about 80% and of this, about 70% consisted of quartz grains, the remainder being flint chips and broken oolith shells. A wind-blown origin might be inferred for some of the thin discontinuous layers but the more continuous seams may be of an alluvial character. For example, at the top of the Lower Gravel (Alabaster and Straw, 1976, Plate 7A) the layer of fine-sandy silt, over one metre thick and made up of several planar and shallowly cross-bedded units parted by thin seams (1 to 5 cm thick) of sand and gravelly sand, could well represent a flood-plain, over-bank deposit (Plate 3). Indeed each silty layer might indicate a temporary break in accretion of the sands and gravels related to seasonal conditions or to migrations across the valley floor of active stream zones. The source of the silt, if largely water-borne, can be sought again in Lower Cretaceous rocks, particularly the Roach beds and Upper Tealby Clay out-cropping upstream.

WELTON GRAVELS – UPPER GRAVEL

This division was usually the one wholly exposed along working sections throughout the commercial life of the quarry (Figure 2). In later years its major flint gravel component became more valuable than sand, especially with the continued absence of Chalk.

Over the whole quarry area of 46.6 hectares (0.18 ml^2) it was, like the Lower Gravel, of consistent thickness, generally between 5 and 8 m, forming a virtually horizontal sheet of material, its upper surface lying at c.80 to 85 m OD, across the palaeo-valley floor (Plates 2, 4). It was distinguishable both in composition and structure from the Lower Gravel, and rested unconformably on it. This latter situation, as shown below, reflected more a change in conditions of sedimentation rather than a prolonged period of non-deposition. Nowhere was a subaerial chemically-weathered horizon observed between the two divisions.

The Upper Gravel had two main components – poorly-sorted flint gravels highly contaminated with manganese and iron oxides, and seams and lenses of sandy silts.

The flinty gravels consisted of discontinuous, broadly-interbedded, planar units up to 1.8 m thick of angular and sub-angular clasts less than

7 cm across in a silty sand matrix (Plate 1). Though very similar in composition two sub-types could be determined:

1. Very poorly-sorted and massive, with matrix-supported unorientated clasts.
2. Poorly-sorted, but with faint or weakly-developed layering or inclined foreset bedding indicated by changes in clast size, the presence of thin sandy/silty partings, or weak alignments of clasts.

The former, from its structureless character, appears to have been transported and emplaced by mass movement processes which could have required a water content at least at saturation level. The latter displays features of fluvial flood transport and deposition, and the beds are interpreted as bar core sediments often, in fact, succeeded upward by thin bar-top drapes or overwash sands. The occurrence of the one or the other seems primarily to have been a function of the volumes of water available.

In some sections the gravels appeared as a stack of discontinuous seams, giving the impression of deposition in flattish, lobate, interbedded sheets of material that had not travelled long distances, probably only from the valley sides. Neither the small overall clast size nor the maximum clast size of c.7 cm should be taken to indicate a low energy regime, merely that the transporting processes were capable of moving all available clast material. The striking fact about the Upper Gravel is the predominance of flint. Unlike much of the sand it could not have been obtained from around the postulated headward areas of the palaeo-valley surrounded as they were by flint-free Ferriby Chalk. A new source of flint had to be exploited, as discussed below. Coloration of the flint gravels was very variable, a consequence of irregular diagenetic precipitation of manganese and iron oxides introduced by groundwater movements (Plate 1).

Between 1969 and 1973, four Palaeolithic artefacts and a small number of fossil bones and teeth of elephant, red deer, horse and bison were recovered from the Upper Gravel. These were in secondary context and are described below.

The fine-grained materials in the Upper Gravel, mostly silt and fine sand, although of similar composition differed in character from those in the Lower Gravel. For instance, layers were thicker and appeared more frequently in section, especially in the higher parts of the Upper Gravel. No layers however extended continuously over the whole quarry area.

Most of the silt layers contained a proportion (usually less than 10%) of fine sand, and in section appeared as discontinuous seams and lenses, varying in thickness from 30 cm to mere wisps and stringers. The thicker beds sometimes displayed bedding, in places inclined.

The discontinuous layers seemed to have been deposited in shallow linear depressions less than 60 cm deep. Where sections transected former depressions the layers appeared synclinal, where a section paralleled a depression the layer was longer and planar. However, the contacts of the silts with adjacent beds was usually sharp, often irregular against gravels and not erosional. Although referred to in 1976 as 'cut and fill' features the depressions, in fact, showed little sign of fluvial erosion. Rather they seem to represent original linear depressions on newly-deposited, moundy, drying, gravelly surfaces, some of them utilized by ephemeral run-off of surplus and expelled water. Some of the silts, which 'drape' the depressions rather than filling them, may have been suspended sediment that settled out of stagnant water. However, whether deposited through water or not, the bulk of the silt and fine sand, in terms of particle-size distribution, falls well within that for aeolian sediments. Their association with the shallow depressions can then be explained in terms of the winnowing of fines over uneven, drying gravelly surfaces. Indeed, the successive layers of flint gravel and silts could have resulted from periodic, probably seasonal, events of floods and mass movements, alternating with drying, fluvially-inactive phases when wind action was likely. The very thin wisps and strands of silt may have accrued from surplus water expelled from over-saturated gravel layers after they had come to rest during low-stage conditions.

The most extensive silt-rich deposit (varying from 0.5 to 1.2 m thick) was exposed in the last few years of quarrying immediately below the overburden at the top of the Upper Gravel (Alabaster and Straw, 1976, Plate 7). Particle-size analysis revealed a clay content of c.30%. In 1970, this layer stretched some 70 m along the west quarry section from near the road where it was cut out by a chalky diamicton and had extended formerly about 50 m south from the section (Plate 2). It comprised therefore a sheet of clayey silt over a restricted area of the Upper Gravel close to the northeast side of the palaeo-valley. Although generally massive, and blocky-jointed on drying, thin streaks of fine sand in some exposures revealed inclined bedding. It is possible that, being immediately beneath the Welton Till, it has suffered some loss by glacial erosion and formerly extended more widely. The disposition, internal structure and poor-sorting of the silt argue against it being alluvial sediment or even lacustrine. If wind-blown, it could however be envisaged as material drifted as a sheet by dominant winds (by inference south-westerlies) toward and against the northeast palaeo-valley side, after the fluvially-active zone had migrated away, in the manner of aeolian deposits in some Arctic valleys today.

WELTON GRAVELS – SOURCE OF THE FLINTS

In contrast with the Lower Gravel, flint gravel dominated the Upper Gravel, sand proportionately less did not form discrete beds though it permeated the gravels, and oolitic limonite was less conspicuous, whereas silt-rich materials were present in thicker and more frequent layers.

It was claimed above that during aggradation of the Lower Gravel, erosion of particular Lower Cretaceous outcrops upstream could account for the presence of the large quantity of rounded quartz sand and the prolific limonite, and that the moderate amount of small-sized flint was derived from soil erosion and creep on valley-sides rather than direct stream erosion of Chalk bedrock.

During Upper Gravel deposition it would seem that the supply of sand and limonite was much reduced, while that of flint was greatly increased. Selective removal of chalk from the Upper Gravel on a large scale after deposition does not seem feasible. The absence of chalk in the Upper Gravel argues against large scale erosion of Welton Formation Chalk upstream. The weak development of fluvial sedimentary structures in the Upper Gravel also points to lack of powerful permanent or even semi-permanent stream activity within the valley. In flood conditions energy was seemingly spent more on transporting material than on erosion. Because it is unlikely that any other flint-rich sediment was available within the immediate confines of the palaeo-valley, a source for flint already released from the Chalk must be sought in the wider catchment. This can only be the upper slopes and broad interfluves.

A long period of subaerial weathering including pedogenesis, under a vegetation cover, probably for many tens of thousands of years on these low-gradient areas of Welton and Burnham Formation Chalks prior to glaciation, may be presumed to have produced a residual, chalk-free regolith analagous to the 'clay-with-flints' of southern England. After such a long period of time flint fragments could have been reduced considerably in size from the nodules and slabs found in the Chalk.

The regolith's thickness and flint concentration are not known, but its mobilization and transfer downslope could have supplied the flints and silts of the Upper Gravel. It is estimated that some 5.8 ml^2 (15 km^2) of regolith-veneered surfaces subsequently modified by glacial erosion, adjacent to the Welton palaeo-valley could have provided flints under appropriate circumstances. Such provision had not occurred during erosion of the palaeo-valley nor during aggradation of the Lower Gravel, when groundwater circulation and spring-sapping in the valley heads and soil formation and creep on slopes were the dominant sediment-producing processes.

The only transportational processes that could translate the upland flints to the palaeo-valley were those involving mass movements, particularly gelifluction. Impoverishment of vegetation, existence of permafrost or at least of seasonally-frozen ground, and availability of snow-meltwater would permit activation of the residual flinty layer allowing its constituents to move downslope eventually to pass on to and out over the valley floor as debris flows. Such physical conditions, together with some reworking and incorporation of Lower Gravel materials especially the sands, are precisely those inferred for production and accretion of the Upper Gravel. Activation and disaggregation of the residual regolith may also have contributed to the greater volume of fine-grained materials found in the Upper Gravel. The residual layer would have had a silty rather than sandy matrix which would descend with the flints to be reworked, with fines available within the valley, by water and wind into the many seams and lenses. Distantly-derived loess may also be a component of the sediments.

THE UNCONFORMITY

The contrasts in sedimentary structure and manner of accumulation between the massive and/or weakly-stratified, poorly-sorted flint gravels, and the stratified, better-sorted sands and gravels emphasize the significance of the junction between the Upper and Lower Gravels (Plate 1).

In most observed instances where Upper and Lower Gravels were both exposed the contact was generally undulating and readily distinguished, and in places erosional where the upper material truncated seams of the lower, even 'descending' 2 or 3 m into it, as if 'channelled'. This unconformity had been present over the whole of the quarry area. Nowhere were signs of subaerial chemical weathering detected at this junction, but superficial structures affecting the upper layers of the Lower Gravel were noted at two places – a small ice-wedge cast toward the east end of the 1970 section (Plate 3), and the large complex feature observed in 1957 (Plate 4). The latter, a linear feature, revealed collapse into a void which also involved the Upper Gravel. Adjacent to this feature, the upper layers of the Lower Gravel were deformed and partly intermixed, for which frost action may be invoked. This large structure is best explained in terms of the formation of a ground-ice wedge that penetrated deeply into the Lower Gravel, subsequently buried by lower layers of the Upper Gravel. Melting of the ice, probably a consequence of talik formation beneath a migrating active-stream zone, then produced the void with concomitant collapse of Lower Gravel and some Upper Gravel materials into it.

No intra-formational ice-wedge casts have been seen in the Lower Gravel, but the presence of the structures noted above indicates the onset of permafrost conditions at the end of Lower Gravel aggradation, an environmental threshold of great significance. It is reasonable to assume that permafrost moved upward through the Upper Gravel from year to year, and that the various gravel layers were deposited in springtime over still-frozen surfaces. Permafrost is also invoked to permit 'active-layer' mobilization and transfer of flints from the upland surfaces. The absence of intra-formational ice-wedge casts from the Upper Gravel can be explained by the constant redistribution of the gravels by debris flow and flood events. One was, however, observed at the top of the Upper Gravel in the east quarry.

It can also be claimed that permafrost onset was at least partly responsible for the reduction in supply of sand and ooliths from the headward areas of the palaeo-valley because it would suppress groundwater circulation and spring-sapping. The unconformity, the changes in sedimentary composition and structure reflecting changes in geomorphological

Plate 1. TF28058830, to N (May, 1959). Upper Gravel of weakly-bedded flint gravel, with iron and manganese oxides, over Lower Gravel of layered sands and silts on flint gravel. The grey sands contain much oolitic limonite.

Plate 2. TF28288835, to E (May, 1970). Welton Till on Upper Gravel, separated at the far end by a lens of chalky diamicton. Fossils and artefacts were located sporadically along the section within a zone 1 to 2 m higher than the spade. The road occupies a small meltwater channel.

Plate 3. TF28288835, to N (May, 1970). Unconformable Upper Gravel penetrating alluvial silts of the Lower Gravel in an ice-wedge cast.

Plate 4. TF28098825, to NE (May, 1957). Welton Till on Welton Gravels. The collapse structure contains some Upper Gravel but marks a former linear ice-wedge developed in the Lower Gravel.

Plate 5. TF28128836, to WNW (July, 1970). Calcethorpe Till on Welton Till. The Till base rises over a lens of chalky diamicton resting on Upper Gravel.

Plate 6. TF28668803, to NE (May, 1958, in east quarry). Marsh Till overriding Welton Till along a planar unconformity. Between Welton Till and Upper Gravel is a lens of chalky diamicton..

Plate 7. TF28278835, to N (May, 1970). Massive flint gravel unit of the Upper Gravel with iron and manganese oxides, enclosing an antler tine of red deer (*Cervus elaphus*).

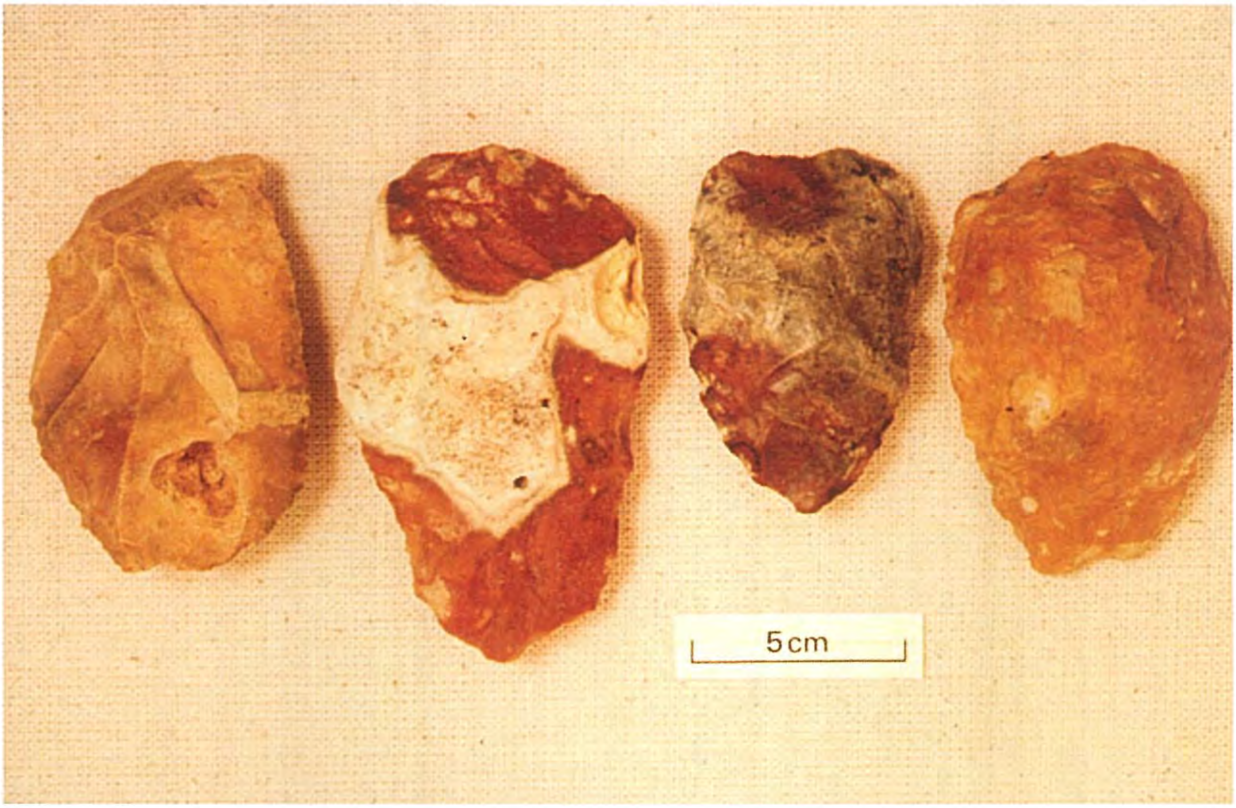

Plate 8. Palaeolithic artefacts found 1970–1973 in the Upper Gravel (Figure 1). Worked flake (left) and three bifaces.

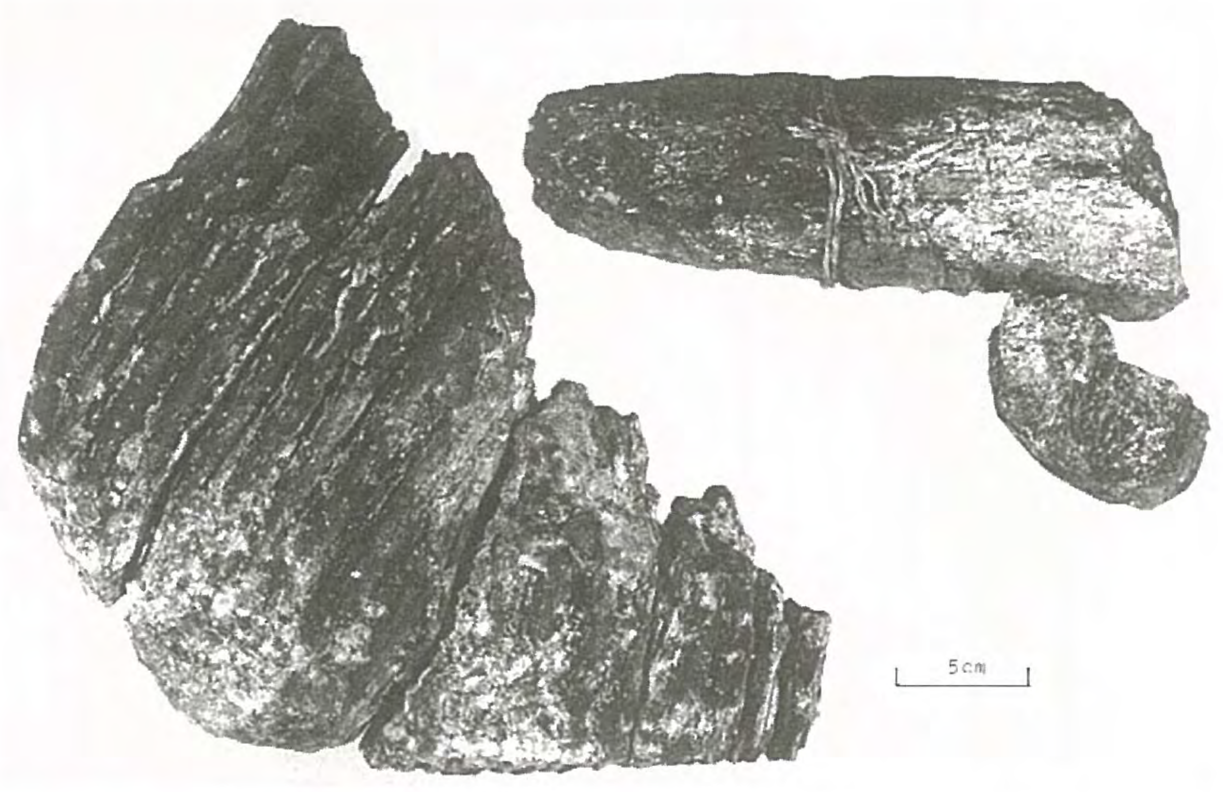

Plate 9. Conjoint upper jaw molars (a few end plates missing) and an abraded tip of a tusk of straight-tusked elephant (*Palaeoloxodon antiquus*). The smaller tooth is heavily worn but only three plates of the larger tooth had grown down to the grinding surface.

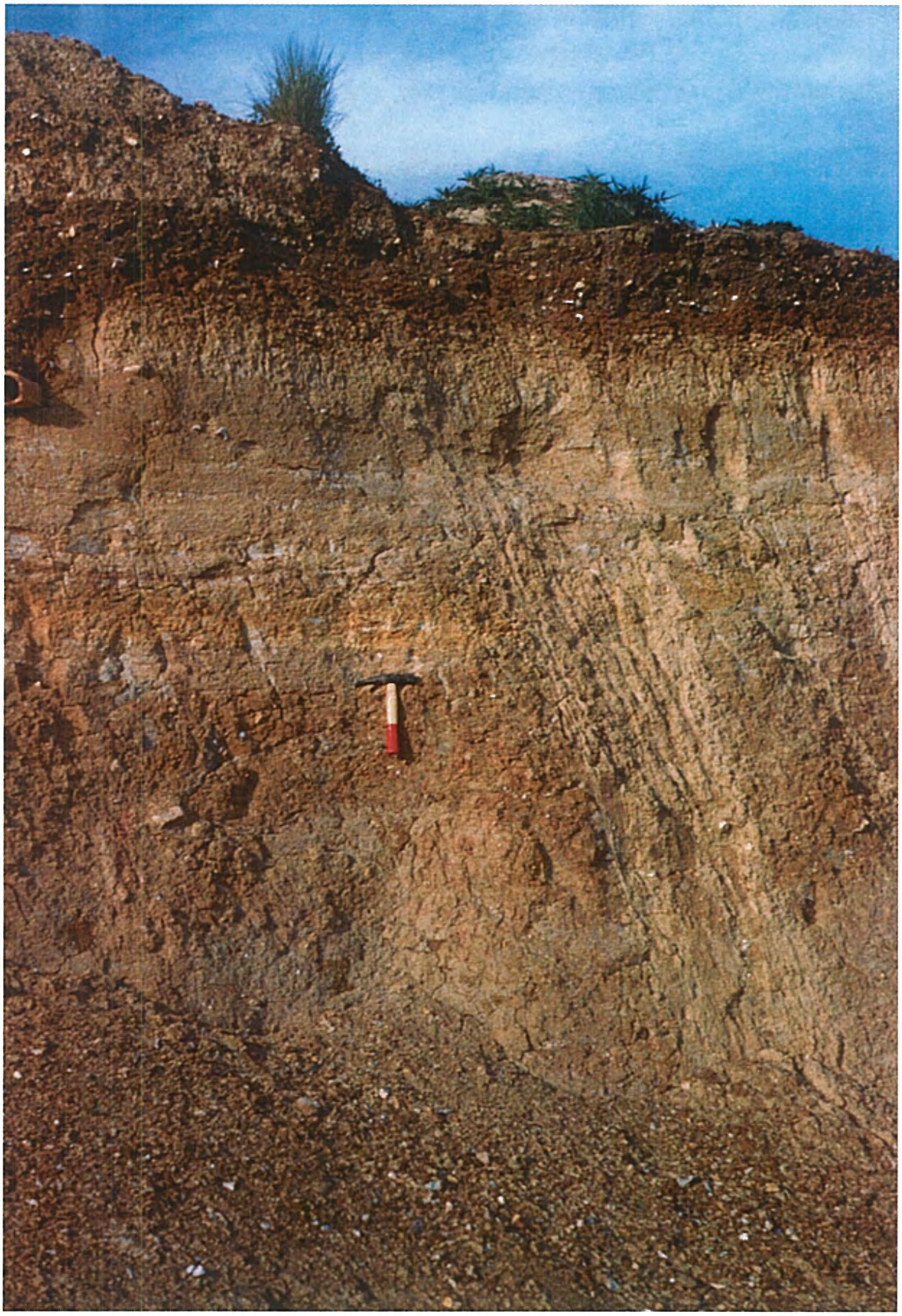

Plate 10. TF27688836, to N (May, 1959). Stratified slope deposits, derived mostly from Calcethorpe Till, on Welton Till (below hammer-head).

processes, the activation of the upland residual layer and its gelifluction downslope can all be ascribed to the onset of permafrost and its persistence until the overspread of glacier ice.

THE CHALKY DIAMICTONS

In several places in the quarry, layers of chalky diamicton overlay the Upper Gravel immediately beneath the overburden of glacial till. In section these appeared as lenses of material up to 5 m thick, with a generally level base but a smoothly arched upper surface (Figure 2). They consisted of chalk rubble with some angular flints, supported in a clayey-silt matrix, in places displaying faint horizontal stratification, truncated by the descending contact with till at each end. The largest such deposit, 50 m wide in section and up to 5 m thick, observed in 1970, lay some 200 m west of the road resting on Upper Gravel (around TF 28108836) (Plate 5). The chalk clasts were fresh, angular and sub-angular, and mostly less than 5 cm across, but a few occurred up to 30 cm. In 1958 another large lens had been noted in the east quarry at the southeast end of the section, some 400 m from the road (Plate 6). At least 50 m wide and 2 m thick, it was identical to the larger western deposit. Earlier still, in 1957, a smaller lens was noted in the western part of the west quarry, and in 1973 chalk rubble was seen to cut out the thick silt lens at the top of the Upper Gravel near the road (Plate 2).

These deposits, mostly of chalk, must have been derived directly from the palaeo-valley sides (particularly the northeast one) and not transported down the valley. The angularity and freshness of the clasts point to mechanical weathering, and the disorientation and thorough mixing of the constituents show them most likely to be the products of gelifluction, spread in varying extents over the surface of the Upper Gravel. By this time reduction in the volumes of flint descending the valley-sides, perhaps indicated by the greater frequency of silt layers, allowed the direct erosion of Chalk. In marking also the cessation of Upper Gravel aggradation it is possible that they herald the arrival of the ice responsible for the overlying tills. The undulating base of the tills, smoothly arched over the lenses of chalky diamicton and descending on to Upper Gravel between them, suggests that the diamicts may have suffered some loss by glacial erosion.

That very cold climatic conditions prevailed at least at the end of Upper Gravel deposition and before the incursion of glacier ice is confirmed by the occurrence, noted in 1973, of an ice-wedge cast some 50 m east of the road in the east quarry which penetrated at least 1.7 m into Upper Gravel below the contact with Welton Till. In terms of change in environmental and physical conditions this contact marks a third significant threshold.

TILLS

The overburden on the Welton Gravels consists entirely of glacial sediments and their derivatives (Plate 5). Understanding of their field relationships improved as the working faces progressed northward, until by the late 1960s the full sequence was revealed (Figure 2).

West of the road the sequence comprises Welton Till, overlain by Calcethorpe Till (Straw, 1964, 1969; Alabaster and Straw, 1976). However, across the central and southern parts of this quarry the Welton Till was covered by slope deposits derived from the *in situ* Calcethorpe Till over the northern part (Plate 10).

East of the road, Welton Till is present in an attenuated form, and is overlain unconformably by the Marsh Till (Figure 2) (Plate 6). This passed upward in places into loamy diamicton and stratified beds.

WELTON TILL

This is a tough, brownish-grey lodgement till, containing many chalk and flint clasts, a proportion striated, and a restricted erratic suite of north British rocks, mostly Jurassic and Carboniferous sandstones and limestones, and some Scottish igneous and metamorphic rocks.

From 1969 to 1973 some 7 to 15 m of the Till were exposed in the sections in the northeast part of the west quarry, resting on Welton Gravels and chalky diamictons with a sharp, undulating, partly erosional contact (Plates 2, 5). Constituents from the Upper Gravel and gelifluctates were never observed higher in the Till than about 1 m above the contact, nor any dragging of the Upper Gravel into the base of the Till. In places, lines of small clasts were strung out along presumed shear planes. It would appear, therefore, that glacier ice advanced over a generally resistant Upper Gravel surface, probably frozen on the evidence of the ‘head’ and ice-wedge cast, prohibiting any further aggradation of gravel and silts. Clast orientation analysis of the Till indicates ice flow from between north and northeast, which strengthens the claim, made above, for the sags along the contact to be regarded as erosional grooves.

The base of the Till over the whole quarry area has been altered diagenetically into an orange-brown, decalcified, oxidized, sandy, flinty layer, between 10 and 30 cm thick (Plates 4, 5). It was seen in every section from 1954 to 1973, and Jukes-Browne described it in 1887 as "a ferruginous layer near the base containing brown-coated flint". Non-development only occurred over some of the chalky 'head' lenses. It is a consequence of 'upward weathering' with air and oxygenated water movement through the permeable Upper Gravel. The layer is indubitably altered Till, and no trace of subaerial chemical weathering nor pedogenesis has ever been detected at the top of the Upper Gravel.

The minor road follows a small north-south valley eroded into the Welton Till (Figure 2). Where, currently, the Till directly underlies the land surface as on the sides of this valley and formerly as eastward of the road before Marsh Till was deposited, the Welton Till has been deeply decalcified and oxidized and takes on a reddish-brown colour, similar to that of weathered Marsh Till.

Through the 1950s and 1960s, Welton Till was observed over the central parts of the west quarry ranging from 3 to 7 m in thickness. It may be recalled that, prior to quarrying, the land surface sloped south (Figure 2) from the high ground behind the 1973 section toward the modern Welton valley and its tributary, creased by shallow gullies. Because the Welton Till thins in this direction (its base remaining broadly horizontal) the slope is considered to be an erosional regrading of the Till surface, a response to the post-Till deepening of the modern Welton valley.

CALCETHORPE TILL

This is a more variable deposit than the Welton Till, although the bulk of it is a highly calcareous deformation till (Plate 5). It now lies wholly west of the road. It contains well-striated pieces of chalk and flint, and a far-travelled erratic suite similar to that of the Welton Till. Generally it is a massive diamicton of chalk and flint clasts, some reaching 60 cm across, imbedded in a brownish-cream matrix of silt, sand and pulverized chalk.

This till facies became exposed in sections only in the later 1960s, with thicknesses of 5 to 10 m as the working face moved northward. In places the till was replaced by bedded chalky and flinty sands and laminated silts, frequently deformed. In others the stratified materials occurred beneath the till, or above. Clearly the Calcethorpe Till is a compound, complex deposit of deformation till and meltout sediments, and its contact with the Welton Till rarely seemed clearly defined. Although difficulties both of accessing sections and of rapid deterioration because of slumping precluded close observation, no weathered horizons or subaerial outwash materials were seen that would have indicated a period of deglaciation following emplacement of the Welton Till.

Ice responsible for the Calcethorpe Till complex must have traversed more of the Wolds Chalk outcrop than that which laid down the Welton Till. It is postulated that the latter arrived first at Welton, from the north-east, thence to be overridden and/or partly displaced by Calcethorpe Till ice from the north, implying no break in the glacial condition.

Before the quarrying of the 1950s and 1960s the Welton Till across the central and southern parts of the west quarry was covered by slope deposits, between 1 and 3 m thick, stratified parallel to the land surface (Figure 2). In places they consisted of grey and brown, silty and/or gravelly materials with chalk and flint fragments, poorly-sorted, and weakly-stratified and 'head'-like. In others they comprised laminated, highly-calcareous, clayey and sandy silts, and silty sands, all regarded as the consequence of sheetwash (Plate 10). As excavation proceeded northward, these materials gave way to *in situ* Calcethorpe Till. Their occurrence marks a late phase in the development of the south-declining slope on the Welton Till, most likely during Devensian time because they directly underlie the present land surface.

MARSH TILL

This now lies wholly east of the road, but originally extended a little toward Welton village, on the southern edge of the Welton Gravels (Figures 1 and 2). Jukes-Browne (1887) recorded it in the two early exposures as "Stiff brown boulder clay of Hessle type" and "reddish-brown clay of Hessle type". Associated regionally with constructional landforms and meltwater channels, the Till is deemed of Devensian age (see below), emplaced by ice that advanced from the east into the South Elkington and Welton valleys. In the east quarry the Till lies above a sharp, westward-rising planar unconformity with the underlying weathered Welton Till (Plate 6) (Figure 2). It thinned northwest from 7 m at the southeast end of the section to nothing just east of the road. Within the lowest 2 m were bands of laminated clays, silts and sands up to 5 cm thick, and parallel strings of small erratics indicating shear structures. These features, together with the planar base confirm that Marsh Till ice rode up a slope on Welton Till to a height of almost 100 m OD. The Till has a rich erratic suite of north British rocks, and a purplish-brown colour weathering reddish-brown. Near the base lie occasional infolded pods of silty and/or gravelly sands.

The disposition of the Marsh Till is of much significance, because it was emplaced after substantial deepening of the Welton valley had taken place, which involved erosion of and slope regrading on the Welton Gravel/Welton Till/Calcethorpe Till complex. A long period of time intervened, therefore, between deglaciation following Calcethorpe Till deposition and the invasion of Marsh Till ice, during which the older Welton deposits were converted from a valley-floor cover into a broad irregular spur between valleys north and south eroded partly into Chalk the east end of which was subsequently overridden by the Marsh Till ice (Figure 1). This ice, therefore, played no direct part in the circumstances surrounding the accumulation of the Welton Gravels and their overburden but, by ponding up some water in the small valley north of the quarry guided its overflow south to cut the little valley followed by the road.

ENVIRONMENTAL CONDITIONS

It is first necessary to examine the origin of the Welton palaeo-valley before discussing the environments of deposition. If, as claimed above, much of the material in the Lower Gravel came from outcrops of Lower Cretaceous rocks, then the palaeo-valley was similar to and takes its place with several dipslope valleys to the north, e.g. the Binbrook, Thoresway and Rothwell valleys, the heads of which today expose inliers of Lower Cretaceous rocks.

Straw (1961a) argued a case for a group of subparallel valleys in the north central Wolds to have been initiated on a wave-cut surface at c.130 m OD, and suggested in 1966 that the upper Bain valleys, following glacial interference, occupy the area once the head of a Welton palaeo-valley.

Whether or not the Wold valley lines were initiated as suggested in 1961, the important point is that eventually, somewhere west of the Welton quarry, Lower Cretaceous materials were being eroded, thence to be transported to and beyond the quarry area. It is also important to note that the palaeo-valley had reached a width of about 600 m or so, and had acquired a fairly level floor at c.60 to 70 m OD some 50 to 60 m below adjacent higher ground. Why did deposition of the Lower Gravel at Welton commence so late in the development of the valley?

An explanation may be offered if it is presumed that for much of the time of its development through the earlier Pleistocene the valley lay wholly within the Chalk. Under woodland conditions and temperate climate, solution and carbonation of the Chalk may have been the dominant processes with stream action, given a sufficiently high water-table, competent enough to remove flint and other insoluble materials from the Chalk out of the valley system. A new situation arose when the valley-head became deep enough to expose the Lower Cretaceous rocks, because large quantities of insoluble sands and limonite ooliths became available. The essential mechanism for release of Carstone and Roach materials in the present-day inliers is spring-sapping, which requires adequate ground-water and an appropriate horizon for seepage. Even if spring activity and overland flow increased because of the exposure of impermeable Upper Tealby Clay beneath Carstone and Chalk, stream competence now became insufficient to remove all sediment from the palaeo-valley. An additional factor may have been a deteriorating climate. The character of the Lower Gravel suggests its deposition by shallow, braided streams, yet chalk does not enter into the bedload material being transported. This can be explained by vegetated valley-sides and little if any direct stream erosion of bedrock Chalk. Such circumstances could operate under a Sub-Arctic nival regime, with boreal vegetation replacing broadleaf woodlands. Although no diagnostic features in the Lower Gravel (other than bedload dominance and braided stream activity) indicated a cold climate, the existence of ground-ice structures in the upper part of the Lower Gravel confirms that permafrost conditions prevailed at the time of, and may well have been responsible for, the cessation of Lower Gravel deposition.

It may be summarized, therefore, that after the deepening and lengthening of the Welton palaeo-valley through both warmer and colder periods of the earlier Pleistocene presumably under a summer deciduous, and perhaps at times a boreal, vegetation cover, exposure and erosion of Lower Cretaceous rocks proved to be a significant geomorphological threshold. As a consequence, increased sediment production overcame the capacity of fluvial transport. This circumstance probably coincided with a period of cooler or cold climate, when greater seasonality in the fluvial regime and development of shallow multiple-channel systems ensured the conditions for Lower Gravel aggradation, and when winter frosts and snow cover would help disintegrate chalk fragments.

The onset of permafrost, marked by the ground-ice structures penetrating the top layers of the Lower Gravel, became a second important threshold. In the event of widespread treeless, frozen ground, spring-sapping would have been suppressed, 'active-layer' processes would have promoted geliturbation and gelifluction processes on formerly stable slopes, and snow-melt run-off would have been concentrated in spring floods with summer drying permitting wind action. Under such an Arctic nival regime with restriction of groundwater flow, sediment production would have been reduced from Lower Cretaceous outcrops but increased from valley-sides and particularly from gentle interfluves within the palaeo-catchment. It is only the activation of flint-rich residual deposits and their sloughing off from these upper areas that can explain the marked dominance of flint in the Upper Gravel and it is no doubt from the matrices of these residuals that much of the silt in the Upper Gravel was derived. Snow-melt saturation of large quantities of flint-rich regolith reaching the palaeo-valley floor could account for the structureless, debris-flow component of the Upper Gravel, and flood reworking of some of these same materials for the bar deposits. Periglacial conditions must have prevailed throughout the period of Upper Gravel accumulation, and the one observed ice-wedge cast in the east quarry near the road supports the case for persistence of permafrost.

Two further circumstances can be explained under this scenario.

First, the increase in silt layers toward the top of the Upper Gravel may in part reflect reduction in the volume of flint fragments coming off the slopes, possibly also even colder, drier climatic conditions.

Second, a notable feature of the Upper Gravel sediments is the small size of the flint fragments – almost invariably less than 7 cm across

(Plates 4, 7). The predominant source of these flints has to be the residual cover on the Chalk interfluves. After some tens, if not hundreds, of thousands of years of weathering, it is surely to be expected that flint clasts in the regolith would be much reduced in size compared generally with flints eroded freshly out of the Chalk. The latter are insignificant in the Upper Gravel.

A third environmental threshold was manifestly the burial of the Welton Gravel beneath glacier ice. After an initial phase of erosion as ice moved across the site, the area was subject to glacial deposition for an unknown length of time first by Welton Till ice and later, additionally, by Calcethorpe Till ice. This composite ice-sheet eventually overwhelmed the whole of the Words, but the manner of its disappearance is not known, though Straw (1966, 1979a,b) argued for widespread stagnation and down-wasting over Lincolnshire and the lower Trent valley. At the quarry the stratified and deformed sediments in the Calcethorpe Till complex support stagnation and meltout conditions. Eventually ice-free conditions returned but by then the headward areas of the Welton palaeo-valley had suffered drastic changes. Calcethorpe Till ice crossing the Wolds had effected largescale erosion (Figure 1), breaching the Cretaceous scarp around Burgh-on-Bain and Biscathorpe and creating gradients and opportunities for post-glacial streams to descend south into the Bain valley (Straw, 1966). These streams became established as the headwaters of the River Bain, and the Welton palaeo-valley ceased to exist as a component of the drainage system of the central Wolds. Instead, streams developed northeast and south of the Welton deposits, eventually producing the valleys which border the quarry area today.

CONTAMINATION OF THE WELTON GRAVELS

A striking visual feature of the Upper Gravel, less so in the Lower Gravel, was the coloration by varying shades of brown and grey, particularly of the gravel seams, because of the precipitation of hydrated ferric and manganese oxides (haematite and pyrolusite).

The streaking of the deposit gave a false impression of stratification, but the bands of oxides by and large passed indiscriminately across unit boundaries. Only occasionally did oxide concentration pick out particular planes of bedding. By contrast the silty layers were unaffected (Plates 1, 2, 7).

The contaminants were not contemporaneous with gravel deposition. They were introduced as post-depositional minerals by groundwater moving essentially through the permeable gravels, necessarily after relaxation of permafrost conditions and presumably after emplacement of the capping Tills. The persistent orange-brown 'sole' at the base of the Welton Till is the consequence of decalcification and oxidation of Till material, brought about by the passage of air and oxygenated water through the Upper Gravel.

The iron derives from chemical weathering of Lower Cretaceous rocks and the manganese from the Chalk, but their mobilization in soils and sediments requires moderately acid environments, possibly those that could be produced under boreal or temperate woodland vegetation following the disappearance of glacier ice and improvement of climate.

Once in solution these minerals were introduced to the Upper Gravel by groundwater passing laterally through it, and moving vertically within it with the rise and fall of the water-table. Precipitation, in some gravels first of iron then manganese, could have been brought about in vadose situations whenever the water-table fell, especially in an alkaline environment. For example, the excessive deposition in the Upper Gravel at least in the quarry area, might be due in part to the influx of hard water from dissolution of Chalk in the tributary Welton valley to the westsouthwest, and its general absence from the Lower Gravel by the latter's continual location within a phreatic zone.

The light coloration of some zones of the Upper Gravel may simply represent its original condition. It seems very unlikely, in view of the stability of the oxides after precipitation, that selective sub-surface leaching of these minerals would take place. The sedimentary character of the paler horizons of gravel, usually no different from that of contiguous brown or grey gravels, seems to have had no influence on precipitation.

Apart from short-term seasonal fluctuations in the water-table, long-term changes could be related to valley-deepening at and east of the quarry through the Tills to expose the Gravels and allow seepage and spring action, and also to glacial obstruction of the modern Welton valley on two occasions in the Devensian. Such vagaries might well be responsible for the over- and under-concentration of the oxides in roughly horizontal zones.

FOSSILS AND ARTEFACTS

Bone fragments, teeth and tusks of temperate animals, and some artefacts were recovered from the Upper Gravel during the last few years of gravel extraction, near to the northeast side of the palaeo-valley (Plates 7, 8, 9) (Figure 1). All are now held by The Collection, Lincolnshire County Council. Although their discovery was fortuitous and within a small area, no similar items had been found or recorded previously. There is no more reason to suppose that similar materials were necessarily scattered indiscriminately through the Upper Gravel than that the finds truly indicate a restricted distribution of such materials. The recorded finds (Alabaster and Straw, 1976) were taken from two parallel worked faces about 6 m apart during 1969 to 1973, over a maximum length of 42 m on the southern section (Plate 2). Of the four small Palaeolithic artefacts, two hand-axes were taken from the sections, and one hand-axe and a worked flake were found nearby on spoil heaps. The mammal fossils were mostly of elephant (*Palaeoloxodon antiquus*) including a complete tusk 2.2 m long , two conjoint molars and a part of a third, together with part of an antler of red deer (*Cervus elaphus*), two astragali of a large deer (*?Megaloceros giganteus*) and cheek tooth fragments of horse (*Equus* sp.). Similar items may have been destroyed by excavation before the section was worked to its 1970 position and also to its 1972 position.

Although lying within a relatively narrow vertical zone (1.5 to 2 m) the fossils and artefacts were not located within a single sedimentary unit. All were recovered from the upper parts of thick gravel units (Plate 7). Being in different units indicates emplacement in different phases of deposition, even if they came from a single source, spread probably over periods of time measured in years rather than days.

In 1976, the fossils and artefacts were claimed to have been derived, on several counts.

1. Identified as of temperate animals, the fossils could not have lived in the Arctic environment deemed to have prevailed during aggradation of the Upper Gravel.
2. Excepting the large elephant tusk and the conjoined molars, the fossils and artefacts showed much evidence of mechanical damage, consistent with abrasion during transport.

3. The seemingly random dispersal of the fossils along the sections (obviously 3D within the deposit) could not indicate positions where the animals died.
4. The tusk and the conjoint molars did not have to be transported by running water in a stream.
5. The two hand-axes found in the sections showed signs of abrasion, were approximately 30 m apart, and lay within different gravel units.

In contrast to other fossils, the elephant tusk and the conjoint molars were relatively less worn and the possibilities existed that they had travelled shorter distances or were even *in situ*. However, the scatter of the remains and the likelihood that more than one animal was represented militated against the latter situation. Indeed, even if the tusk were in situ, the rest of the elephant had been dispersed.

It was demonstrated above that the Upper Gravel was, unlike the Lower Gravel, not a deposit laid down by free-flowing, braided streams, but rather one which resulted from the bulk transport of the flint gravels by flood bar and debris flow processes. There is the strong likelihood, therefore, that the fossils and artefacts were 'rafted' into their secondary locations from their original positions. Regardless of the size of the elephant fossils, their density would have been considerably less than that of the enveloping saturated flint gravel, and it becomes significant that they all lay within the upper parts of the host gravel units. When discovered in section, the elephant molars were surrounded by much friable bone. If this were originally skull material, then it could have protected the molars from abrasion during transport. It is firmly believed, therefore, that all the mammalian fossils and the artefacts had been moved from an older, temperate, and to date undiscovered, deposit.

Discovery of the fossils and artefacts was fortuitous, none having been found before 1969. It is acknowledged that others may have been unobserved, and destroyed during excavation in other parts of the quarry, but it might be a real circumstance that they occurred in a relatively small area near the northeastern valley-side (Figure 1). If it is accepted that down-valley transport is not obligatory, and in the likelihood that much of the flint gravel descended the valley sides, then the original location of fossils and artefacts might lie not too far to the north or northwest from where they were found. The fact of their incorporation in different gravel units across the 42 m width of the sections might indicate that they were carried by several diverging debris flows into splayed spreads of sediment over the northern valley floor, over a period of no more than a few years.

CHRONOLOGY

The Marsh Till represents the earlier of two advances of ice during the Devensian stage that reached the vicinity of the Welton and South Elkington areas (Figure 1) (Straw, 1957, 1958, 1961b, 1979c, 1980, 1991). Ascribed to the Early Devensian, it may have been emplaced during OIS 4 (Figure 3). Recent amino-acid dates (Bowen et al., 2002) confirm that Devensian ice reached as far south as north Norfolk before the Last Glacial Maximum which was firmly placed at c.22,000 years BP (before present). A date of c.40,000 years BP was indicated for the earlier advance, and it was this which deposited the Marsh Till at Welton quarry and village. The Last Glacial Maximum is marked by the Hogsthorpe Moraine east of Alford (Straw, 1957, 1961; Bowen et al., 2002) and by the morainic and outwash deposits at South Elkington, about one mile east of the Welton limit.

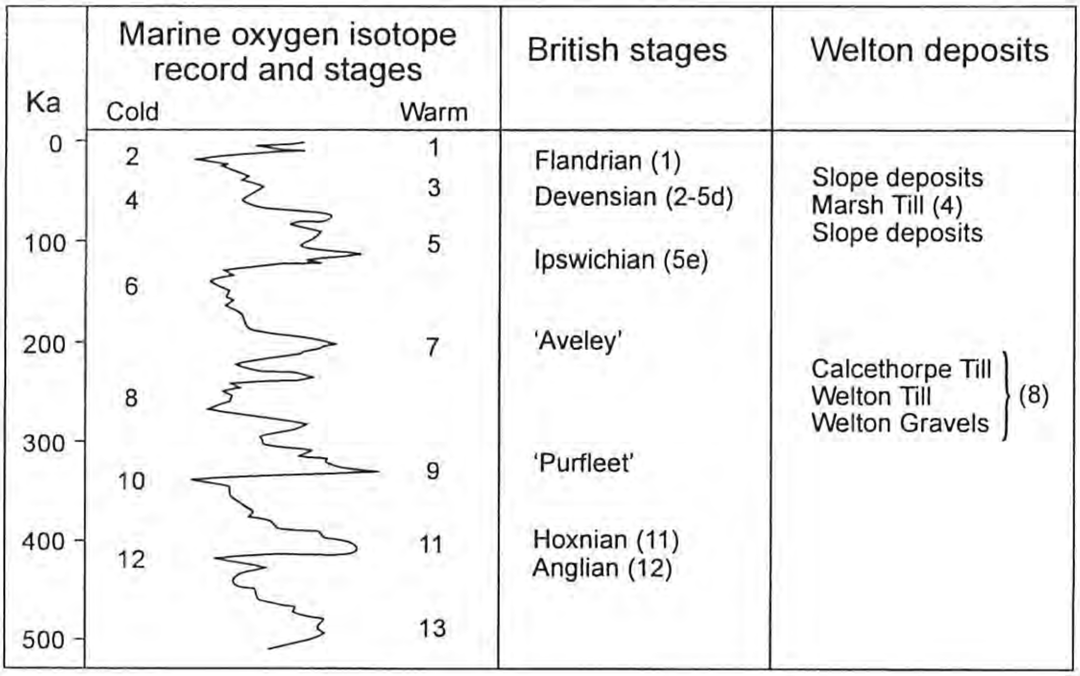

Figure 3

Apart from interfering with groundwater flow through the Welton Gravels and ponding the Welton valley drainage (diverting it through the Welton Vale meltwater channel), neither glacier had any direct part to play in the accumulation of the Welton Gravels and Tills, although they would have had some effect on precipitation of iron and manganese oxides in the Gravels.

In the east quarry the earlier ice demonstrably rode up the east end of the eroded mass of older deposits, leaving Marsh Till resting on weathered, reddish-brown Welton Till. East of the quarried area, attenuation of the Welton Till would have allowed the ice some contact with the Welton Gravels (Figure 2). Indeed, in moving westward from Louth toward South Elkington and then Welton, the ice would have crossed and perhaps in part assimilated a variety of valley-floor and slope deposits both temperate and periglacial.

A long period of subaerial erosion preceded the Devensian glaciation during which, not only the present Welton valley and other branches of the River Lud system were deepened and enlarged, but most of the Calcethorpe and Welton Tills were removed from the Wolds in general. The length of time required for these landscape changes is impossible to determine precisely, but estimates can be made depending on the age given to the Calcethorpe and Welton Tills. In 1976, adopting the standard usage of the time and with the mammalian fossils being provisionally allocated to the Hoxnian Interglacial (Alabaster and Straw, 1976), the Welton and Calcethorpe Tills were considered to have been laid down during the 'Wolstonian' Glaciation. Today, based on OIS geochronology, this glaciation could fall in any of Stages 6, 8 or 10 (Figure 3).

In a 'Revised Correlation of Quaternary Deposits of the British Isles' (Bowen et al., 1999) the Welton Till was tentatively placed in OIS 6 and, perversely, the Calcethorpe Till in Stage 12. This incorrect allocation (because the Calcethorpe Till lies above, not below, the Welton Till) (Plate 5) was challenged by Straw (2000) who preferred OIS 8 as the probable stage in which the Welton Till and Calcethorpe Tills were emplaced (Figure 3). On this reckoning the long period of pre-Devensian erosion approached some 200,000 years and would have included the temperate OIS 7 and 5e stages. It would have been nearer 400,000 years if the Tills belong to O1S 12.

The obvious limitations to relative dating emphasize the need for so-called absolute dates for the deposits. The mammalian fossils are too fragmentary and in secondary context, and the species represented are too wide ranging within the Quaternary to give any precision. The same difficulties apply to the artefacts. Most potential lies in the application of specific geochronometric or numerical techniques to appropriate material within the Welton Gravels.

SEQUENCE OF EVENTS

Based on the foregoing descriptions and discussions a succession of events bearing on and relating directly to the Quaternary deposits and landforms at Welton-le-Wold can be postulated (Figure 3).

1. *Pre-Anglian* (? to OIS 13) – probable late Tertiary and early Quaternary establishment of the lines of the Wold dipslope valleys which would have been simple in form, and eroded wholly within the Chalk.
2. *Glaciation* (OIS 12) – complete glacierization of the whole of Lincolnshire during the Anglian stage. The amount and location of any erosion is not known and no deposits remain. Following deglaciation, drainage was re-established along a linear depression coinciding with a pre-glacial valley to begin the development of the Welton palaeo-valley.
3. *Long period of subaerial denudation* (OIS 11–9) – temperate climatic conditions and deciduous woodland would characterize the Hoxnian and Purfleet Interglacials, but cool or cold conditions during OIS 10 may have introduced SubArctic boreal forest, or even tundra. Prevalence of chemical weathering led to the formation of a substantial residual regolith on low-gradient Wold surfaces. General enlargement and deepening of the Welton palaeo-valley took place until its floor stood at c.65 to 70 m OD at the quarry some 50 to 60 m below adjacent high ground, although fossil- and artefact-bearing deposits accumulated somewhere north or northwest of the quarry, perhaps as a terrace fragment.

4 *Cold stage* (OIS 8)
   (a) *Deterioration of climate and return of boreal forest.* More mechanical weathering and valley-head exposures of Lower

Cretaceous rocks increased sediment yield beyond the capacity of the stream to remove all rock waste. As SubArctic nival conditions became established, spring floods were more prevalent and the stream assumed multiple-channel behaviour as aggradation of the Lower Gravel proceeded.

(b) *Progression into continual Arctic nival conditions with treeless, probably tundra, vegetation.* The onset of permafrost and 'active-layer' processes involving gelifluction and the mobilization and transfer of high-level residual deposits allowed the formation of the Upper Gravel.

(c) *Glaciation of the Wolds* (and all Lincolnshire). Ice first advanced southwest to south over the lower part of the Welton palaeo-valley (Welton Till) and later south–southeast and south over the upper part (Calcethorpe Till) with some overlap.

5. *Erosion* (OIS 7–5) – excavation of the modern Welton valley and its left-hand tributary along the south and west sides of the quarry area and general deepening and enlargement of the central Wold valleys. Temperate climatic conditions prevailed through the Aveley and Ipswichian Interglacials, with a colder interphase (OIS 6). Erosion and some regrading of the surface affected the quarry area, while alluvial sediments were spread along the valley floor below Welton to and beyond Louth.
6. *Glaciation* (OIS 4) – about 40,000 to.45,000 years BP during the Devensian stage, ice advanced from the Humber, over the Marsh and on to the eastern Wolds, and down to north Norfolk. Marsh Till was deposited in the east quarry, and Welton valley drainage was ponded with overflow initiating the Welton Vale meltwater channel. Periglacial processes produced slope deposits derived mainly from Calcethorpe Till over the central and south quarry areas, west of the ice front.
7. *Less extensive glaciation* (OIS 2) – later in the Devensian stage, about 22,000 years BP, ice again crossed the Marsh on to the eastern parts of the central Wolds. Ice reached South Elkington depositing morainic gravels and sands around that village, and diverting the Welton stream south and irreversibly through the Welton Vale channel. Gullies developed over the quarry area, with gelifluction on slopes.

8. *Temperate stage* (OIS 1) – establishment of woodland cover and soil formation over all deposits in the Flandrian, and alluviation along stream courses.

CONCLUSION

It remains to emphasize the uniqueness of the Welton deposits within the Wolds and their special character in the wider context of eastern England.

The Welton Gravels represent the sole occurrence in the Wolds, and perhaps in eastern England at large, of a valley-floor deposit sourced entirely within a specific catchment, covered by glacial tills of pre-Devensian age. At Biscathorpe, four miles to the southwest, Calcethorpe Till overlies thick gravels and sands, but these belong to an outwash sandur and contain much chalk (Straw, 1966). Within eastern England, a similar situation exists only in the Bytham valley of southwest Lincolnshire, though here pre-Devensian till rests on sands and gravels considered to have been laid down by a major Midland river in pre-Anglian time (Rose, 1995).

The flint-rich, sandy and chalk-free composition of the Welton Gravels was the prime reason for long-continued commercial quarrying, and it is through this activity that exposures of the Gravels and Tills became available. No other chalk-free gravels occur in the Wolds.

Survival of the Welton Gravels is also exceptional. Ice responsible for the Welton and Calcethorpe Tills flowed across the valley, not along it. Had ice-sheet flow coincided with valley alignment, then it is unlikely that much valley-floor sediment would have survived. Yet, other Wold valleys to north and south had alignments transverse to ice flow and no deposits survive. This might be because of thorough subsequent erosion but it might also indicate that none of these other valleys had, pre-glacially, uncovered inliers of Lower Cretaceous rocks in their headward areas (although many have today) and had not therefore crossed that vital threshold in terms of sediment supply. The uniqueness of Welton Gravels' survival may, therefore, simply rest on the singularity of their production.

The occurrence of Palaeolithic artefacts, even if they are in secondary context, in sediments indubitably covered by pre-Devensian glacial material is a rare archaeological circumstance (Wymer and Straw, 1977), unique in the Wolds and exceptional in eastern England.

The Welton deposits are claimed above to have been deposited during a continual phase of deteriorating climate, recording both the onset of permafrost and the incursion of glacier ice. This is a most important characteristic of the deposits, especially as they contain fossils of temperate mammal species. There is no sedimentary evidence for a warm break in the worsening environmental conditions. Abrasion of the artefacts supports the view that they too were derived, presumably from a pre-Welton Gravels deposit.

Finally, the superimposition of Marsh Till (Devensian) on much older Welton Till and Gravels is unique in Lincolnshire. Indeed only in the Dimlington cliffs on the Holderness coast does a similar situation exist, where Skipsea Till (Devensian) rests on Basement Till (Catt, 1991). Profound landscape changes took place in the period represented by the basal unconformity of the Marsh Till, recorded more in land-forms than sediments. This last point serves to emphasize that a comprehensive account of the Quaternary deposits at Welton-le-Wold must include consideration of the geomorphological evolution of the wider area.

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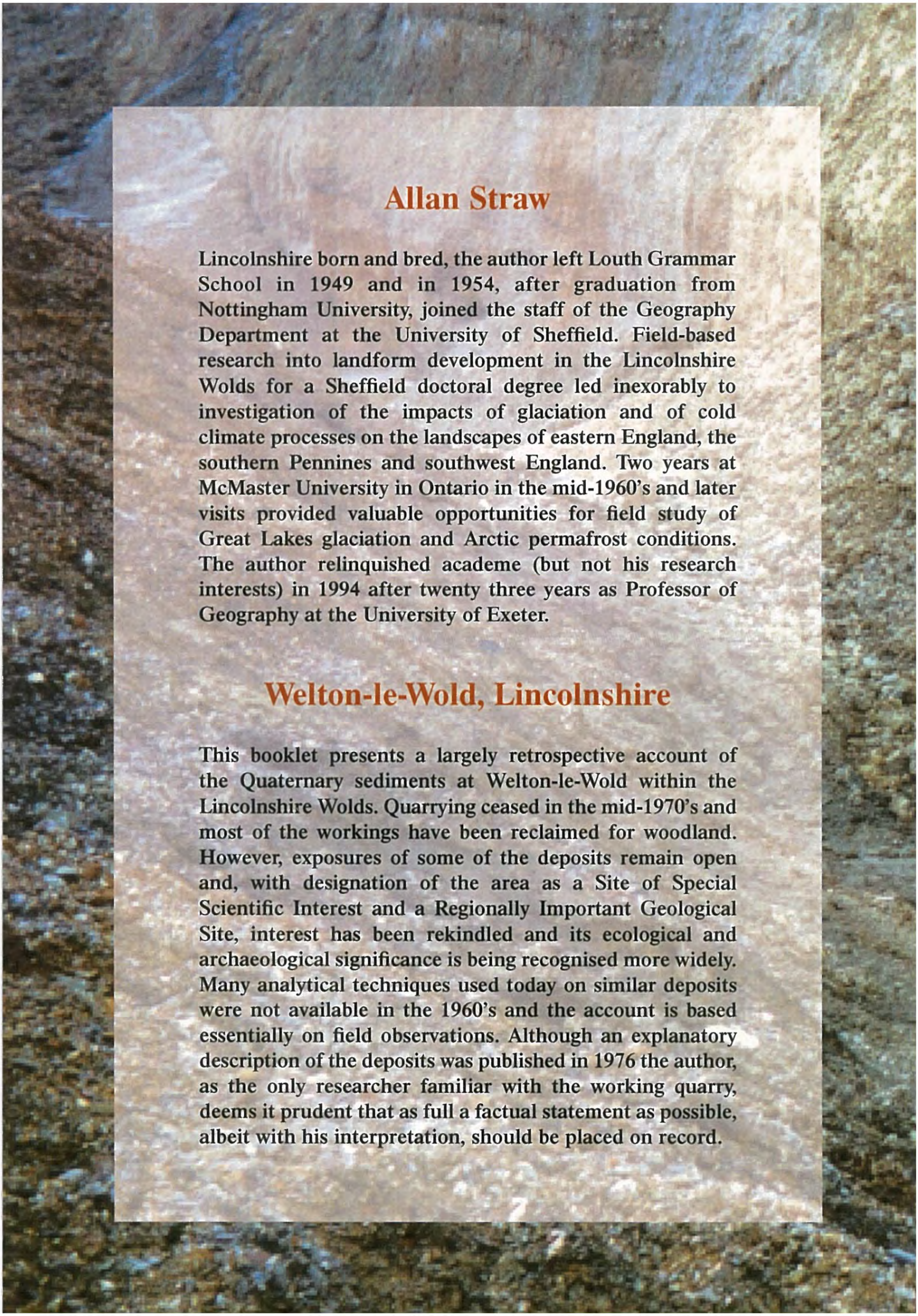

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Lincolnshire born and bred, the author left Louth Grammar School in 1949 and in 1954, after graduation from Nottingham University, joined the staff of the Geography Department at the University of Sheffield. Field-based research into landform development in the Lincolnshire Wolds for a Sheffield doctoral degree led inexorably to investigation of the impacts of glaciation and of cold climate processes on the landscapes of eastern England, the southern Pennines and southwest England. Two years at McMaster University in Ontario in the mid-1960's and later visits provided valuable opportunities for field study of Great Lakes glaciation and Arctic permafrost conditions. The author relinquished academe (but not his research interests) in 1994 after twenty three years as Professor of Geography at the University of Exeter.

Welton-le-Wold, Lincolnshire

This booklet presents a largely retrospective account of the Quaternary sediments at Welton-le-Wold within the Lincolnshire Wolds. Quarrying ceased in the mid-1970's and most of the workings have been reclaimed for woodland. However, exposures of some of the deposits remain open and, with designation of the area as a Site of Special Scientific Interest and a Regionally Important Geological Site, interest has been rekindled and its ecological and archaeological significance is being recognised more widely. Many analytical techniques used today on similar deposits were not available in the 1960's and the account is based essentially on field observations. Although an explanatory description of the deposits was published in 1976 the author, as the only researcher familiar with the working quarry, deems it prudent that as full a factual statement as possible, albeit with his interpretation, should be placed on record.