CHAPTER 3

DESK STUDY:
REVIEW OF LITERATURE AND PREVIOUS RESEARCH

Part 1: Introduction & description of Pleistocene deposits within the study area

3.1. The Pleistocene – an overview

The Pleistocene spanned approximately 2 Ma and was marked by a series of alternating glacial and interglacial conditions. The marine oxygen isotope stratigraphy (MIS) curve in Figure 3.1 shows that Early Pleistocene high frequency climatic oscillations of relatively low amplitude progressively gave way to a cycle of longer periodicity and higher amplitude leading into the beginning of the Middle Pleistocene. The increase in amplitude is thought to correspond to greater fluctuations in ice volume (Boulton, 1992). At the same time, the general climatic deterioration of the last 2.7 Ma continued (Gibbard & Kolfschoten, 2004). Throughout the entire Middle and Late Pleistocene, these large amplitude, low frequency oscillations provided the conditions that allowed the formation of great continental ice sheets. The early Middle Pleistocene saw the arrival of the Anglian Glaciation. This occurred between the late Cromerian Complex dated at around 500,000 years ago and the Hoxnian Interglacial thought to commence at sometime between 470,000 and 400,000 years ago (Bowen, 1999). During this glaciation, an extended ice sheet covered most of Britain, the southern limit of which reached the outskirts of north London, approximately 30 km south of the present study area. After the decay of Anglian ice, fluvial conditions returned and interglacial deposits of Hoxnian age were laid down. Across Hertfordshire, these are found to occupy kettle-type hollows developed in the glacial deposits. A further climatic deterioration after the Hoxnian may have been responsible for widespread glaciation in Midland England, possibly reaching the western part of the study area (Clark *et al.,* 2004). The Ipswichian Interglacial marks the beginning of the Late Pleistocene, followed by the last glaciation, the Devensian. Ice sheets of the latter advanced only as far south as north Norfolk (Catt, 1991), the area studied here experiencing only periglacial conditions at this time.

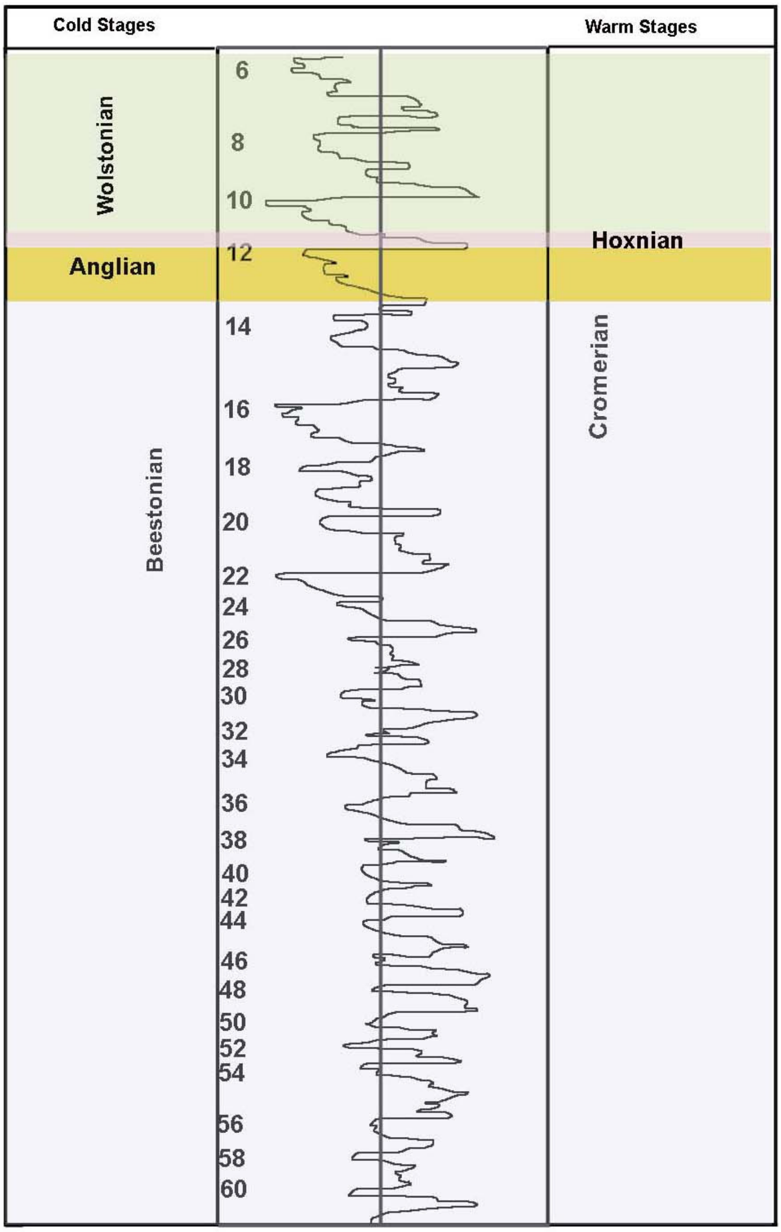


Figure 3.1. Marine isotope curve for the Early & Middle Pleistocene.

(adapted in part from Gibbard & Kolfschoten, 2004).

3.2. Pre-Anglian glaciation

The marine oxygen isotope record (Figure 3.1) clearly shows several major cool phases prior to the glaciation of MIS 12. It would not be surprising, therefore, to find evidence of an early glaciation in southeast England. A marked event is seen at MIS 22 in the Early Pleistocene and another at MIS 16 in the early Middle Pleistocene. Evidence is found across Northern Europe of a major glaciation (Don glaciation) in MIS 16 (Turner, 1996) and a recent re-appraisal of the Happisburgh and Corton Tills of northern East Anglia has led to the suggestion that they also originate from this stage (Hamblin *et al*., 2000; Rose in Clark *et al*., 2004). These tills are traditionally believed to have been deposited during the Anglian Glaciation (MIS 12) (Bowen, 1999) and the proposed new stratigraphy remains controversial (Banham *et al.,* 2001; Gibbard in Clarke *et al.,* 2004).

Since the beginning of the last century several papers have been published regarding various deposits that have been thought to represent a pre-Anglian glaciation. Those that fall within the area currently under study are summarised below. These deposits mainly comprise those of the Chiltern Drift and the Pebbly Clay Drift, both of which were at one time attributed to the Beestonian glaciation (Catt, 1978).

Subsequent work has completely discounted any evidence of a pre-Anglian glaciation within the study area. However, erratic lithologies found within early gravels in the western part of the early Thames catchment (Section 3.4) are taken to indicate a minimum of 10 glacial episodes during the Early and early Middle Pleistocene (Hey, 1976; Green *et al.,*1982; Rose *et al*., 1999). These gravels may therefore provide evidence of multiple pre-Anglian glaciations of North Wales, although Green *et al.* (1982) were convinced of a pre-Anglian glaciation of the South Midlands.

3.2.1. Chiltern Drift

These deposits are found on the backslopes of the Chiltern Hills and form part of the Plateau Drift of Wooldridge (1938). They were also investigated by Sherlock & Noble (1912) who claimed that ice had passed over the Chilterns, depositing the Clay-with-Flints. The latter were subsequently re-interpreted by

Sherlock (1924) as deposits from a local Chiltern ice-cap. Wooldridge suggested that this ice advance was responsible for an early diversion of the proto-Thames before the final Anglian diversion into its present course (Wooldridge, 1938; Baker & Jones, 1980). Shotton (1986) claimed that although the Plateau Drift found on the Cotswold dipslopes presented evidence for a possible Baventian glaciation, evidence for a glacial origin of the Chiltern Drift was lacking. A detailed study by Moffat & Catt (1986) re-interpreted this deposit as the result of soil development and clay enrichment of sediments originating by fluvial transport before the deposition of the Westland Green Gravel.

3.2.2. Pebbly Clay Drift

This was recognised by Thomasson (1961) during a soil survey of southeast Hertfordshire, on the basis of its characteristic lithological and mineralogical composition and far-travelled component. The deposits found on the South Hertfordshire Plateau were examined in detail by Moffat & Catt (1982), who considered them to result from soil development before and after deposition of the chalky Anglian till. Avery & Catt (1983) also undertook an investigation of the deposit in Northaw Great Wood by particle size, heavy mineral and fabric analyses. Their results indicated that at this site it is weathered chalky till.

3.3. Pre-Anglian relief

The main features of the Chalk escarpment were probably in existence prior to glaciation. However, it appears that the ice had a greater effect to the northeast of the Hitchin Gap, where the peaks were overtopped and eroded substantially to form broad low irregular hills (Embleton & King, 1975; Clayton, 2000). Linton (1963) described this as a “profound modification of form and of erosion on the most massive scale”. Indeed, the crest of the escarpment within the eastern part of the study area is suggested to have been approximately 10 m higher and located between 10 - 26 km to the northwest of its present position prior to erosion by the Anglian ice sheet (Clayton, 2000). A similar proposal was made by Wooldridge & Smetham (1931) who considered substantial planation of the chalk had occurred here, suggesting that the scarp face had been eroded back by 6.5 km. The latter authors also considered erosion by the ice to be responsible for the formation of the bench of Chalk Marl at the foot of the scarp.

However, Boreham (2002) considered periglacial processes to have played a large part in the degradation of these hills and Sparks (1957) preferred to believe the subdued topography of the North Hertfordshire Chalklands to be a relic of a pre-glacial landscape.

The Hitchin Gap itself was probably present in some shape or form prior to the Anglian Glaciation. Early work by Bloom (1934) led him to remark “The fact that can be stated with most certainty … is that the Hitchin Gap existed before the advance of the northern ice sheet”. The Gap appears to have been exploited by the ice during the early part of the glaciation when a lobe advanced down the Stevenage and/or Hitchin Valley, possibly reaching the Vale of St Albans in the south (Sherlock & Pocock, 1924; Clayton & Brown, 1958; Gibbard, 1977). Later, during the Anglian maximum, ice covered the valleys completely and overrode all but the highest Chiltern Hills to the west of the Gap.

There are however, considerable differences in the two channels contained within the Gap, probably resulting from different histories. The evolution and character of these two channels is dealt with in Section 3.8.2, but it may be that only the Stevenage Valley was in existence prior to the Anglian glaciation, the Hitchin Valley perhaps marked by a minor tributary stream and/or a weakness in the chalk escarpment (Brown, 1959).

The Northeastern Plateau appears be covered with considerable depth of Pleistocene deposits, the sub-Anglian contours indicating an irregular surface ranging from 15 m to 60 m O.D. (Sparks, 1957). It is unclear as to the exact character of the pre-glacial surface, much of which may have been subjected to considerable erosion during the early Anglian, prior to till deposition.

3.4. Pre-Anglian drainage

The regional drainage pattern of the early Middle Pleistocene bore very little resemblance to that of the modern day. Two major river systems, the Thames and the Bytham, whose catchments dominated central and southern England, are shown in Figure 3.2. Both rivers ran approximately west to east across the country (Rose, 1994; Rose *et al.,* 2001).

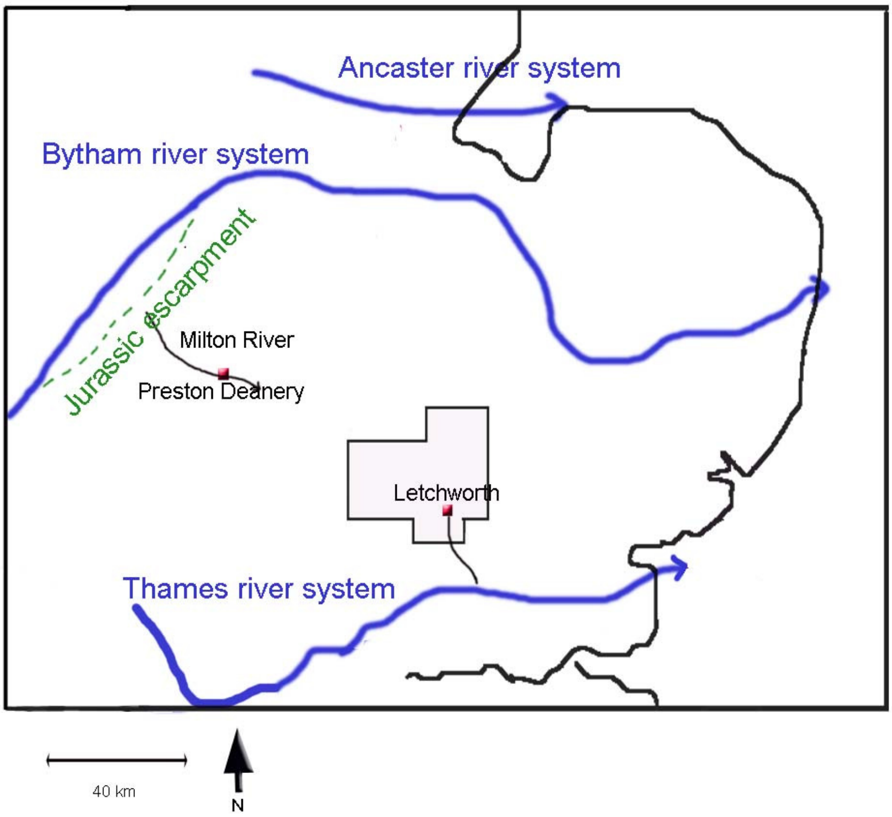


Figure 3.2. Pre-Anglian river systems, showing the position of the Milton Formation in relation to the Letchworth Gravels.

The Bytham river drained the Midlands and southern Pennines (Bateman & Rose, 1994) running west to east across the Fens and on to northern East Anglia and the North Sea (Rose *et al.,* 2001). North of the Bytham River, the Ancaster River, bringing sediment from the north Midlands and the southern Pennines, also drained into the North Sea. Therefore, deposits from both of these rivers lay in the path of the advancing Anglian ice sheet as it passed into the Wash and dispersed in a fan-like fashion across East Anglia. This explains why erratic lithologies from the Midlands are found incorporated into till within the study area.

To the south of the present study area the catchment of the early Thames extended from the South Midlands and flowed through Hertfordshire along the line of the Vale of St Albans, continuing across East Anglia to drain into the southern North Sea.

The earliest Thames deposits are those of the Nettlebed Member (Nettlebed Formation of Rose *et al.,* 1999) part of the Pebble Gravel Formation on the Chiltern backslopes (Gibbard, 1999). These flint-rich gravels are distinct from the vein quartz and quartzite-rich overlying deposits of the Kesgrave Group. The Kesgrave sands and gravels are divided into the Sudbury (early) and Colchester (later) Formations. Differences in lithologies between the latter Formations are believed to reflect changes in the catchment area of the Thames. However, the presence of volcanics from Wales, along with lithologies from the southern Pennines and Welsh borderlands, are thought to indicate contributions from glacially transported material.

It is possible that a precursor of the Ouse Valley was in existence prior to the Anglian glaciation. Horton (1970) traced a series of drift-filled depressions beneath the current Ouse and Ivel Valleys between Biggleswade and Huntingdon, which he felt may have represented part of a drainage system, possibly connected to similar north-south oriented depressions found within the Fen Basin. However, there is controversy over drainage patterns in this area and doubt as to whether the Fen basin was in existence at this time, as described in Section 3.13.

3.5. Letchworth Gravels

During preparation work for the British Geological Survey memoir for Hitchin, an outcrop of gravels captured the attention of Smith (1992). Occupying a limited area north of Letchworth on the eastern side of the Hitchin Gap, these quartz and quartzite-rich gravels are later described by Smith & Rose (1997), who interpreted them as fluvial deposits of a southeasterly flowing river they named the Letchworth River. The stratotype of the Letchworth Formation is at the former Fairfield Hospital (TL204354) shown in Figure 3.3, together with two other sites sampled by these authors to the south. They rest unconformably on the Lower Chalk and although the authors were unable to confirm that these gravels underlie chalky till, subsequent work has proved this to be the case (Cheshire, pers. comm). These pebbly sands and gravels were found by Smith & Rose to lie between approximately 63 and 77 m O.D.

Gravels of an unusual nature in the Letchworth area appear to have been first described by Hill in 1908. His report of gravels of “a different character” on the summit of Wilbury Hill (TL202327) at *c.*86 m O.D. described a section approximately 2.5 m thick overlain by approximately 2 m of loam. Figure 3.3 shows the position of former gravel pits, one of which presumably coincides with that visited by Hill. As can be seen in Table 3.1, these gravels lack Jurassic lithologies, although they contain a good deal of flint and chalk. This gravel was at the time being quarried for use in the construction of Letchworth Garden City, being abstracted from pits lying approximately 0.5 km northeast of Wilbury Hill, where it was present in sections up to 4.2 m thick. Here, Hill noted the gravels were interspersed with layers of current bedded sands with much fine chalk. He noted that “further on” (presumably to the northeast) the gravel passed laterally into sand closely associated with till. Although superposition of the deposits could not be confirmed, Hill considered that there was a “good reason” for believing the sands and gravels lie stratigraphically beneath the till and felt the gravels are probably older than other deposits found locally.

In 1921, Culpin described gravels from a pit he referred to as the ‘Tail’ Pit (TL218275) close to Little Wymondley. He observed a lack of Jurassic limestones and fossils and also reported that the gravels appeared to be

🟪 **Extent of Letchworth Gravel outcrop**

A	Stratotype of Letchworth Gravels (Smith & Rose, 1997)
B C	Further sampling sites of Smith & Rose (1997)
D E	Wilbury Hill sampling sites of Hill (1908)
F	'Tail Pit' of Culpin (1921) & Priest (1921)
G	Ippollitts Pit of Culpin (1921) & Priest (1921)

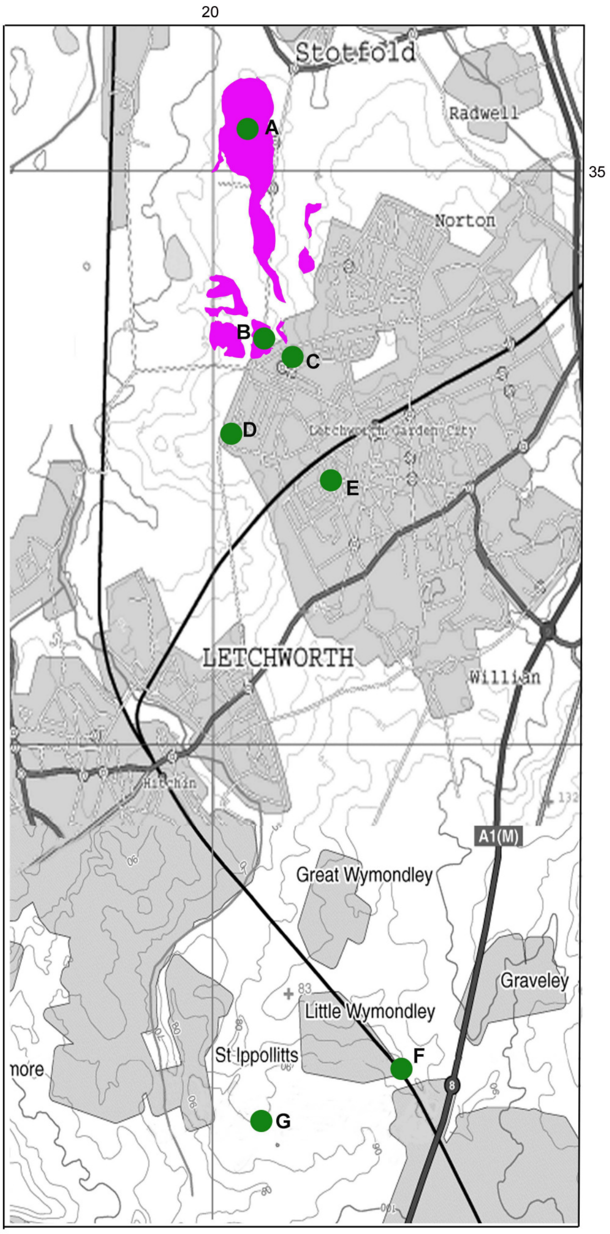


Figure 3.3. Letchworth Gravel outcrop and gravel pits referred to in text.
(adapted from Smith & Rose, 1997).

considerably older than those found in other local pits. A comparison was made between gravels from this pit and those found in Ippollitts Pit (TL206272), both pits lying at *c.*85 m above O.D. In a supplementary note to this paper, Priest (1921) gave detailed description of the lithologies (Table 3.1). The Ippollitts Pit displayed a good range of Jurassic shelly limestones, septaria*, Gryphea, Ostrea* and belemnites in addition to (probable) Old Red Sandstone, Millstone Grit, Bunter quartzites and igneous rocks. In contrast, lithologies found at the Tail Pit, lacked Jurassic material and appeared to contain no notable flint.

3.5.1. Discussion

The gravels described above by Smith & Rose (1997) and those at the Tail Pit all appear to lack Jurassic lithologies, have low flint content and comprise a high proportion of lithologies from the northwest (Table 3.1), although the description by Priest (1921) does not imply a preponderance of quartz/quartzite pebbles. However, it is possible that gravels at the Tail Pit form part of the Letchworth Formation. If this suggestion is correct then this formation extends at least a further 6 km south of the outcrop shown on BGS 1:50,000 Sheet 221 and extends to a higher altitudinal position than suggested by Smith & Rose. The sites investigated by Hill (1908), however, despite being much closer to the outcrop of Letchworth Gravel (Figure 3.3) and also suspected of lying stratigraphically below the till, appear to differ from those above, in that Hill noted this gravel to “consist almost entire of smallish angular and subangular flints and many well-rounded chalk pebbles”. Without a more detailed description of this deposit, it is impossible to comment further on the similarity or otherwise to gravels of the Letchworth Formation. It is interesting to note that the sites of Hill (1908) lie at similar heights to the Tail Pit.

The lack of Jurassic limestones, fossils and chalk, was used to infer a fluvial origin for the Letchworth Gravels by Smith & Rose as these lithologies would not have been able to survive fluvial transport for any great distance. The catchment of the Letchworth River suggested by these authors, is thought to have originally extended to the Triassic bedrock of the southwest Midlands and a route was proposed along the Stevenage Valley to form a northern tributary to the proto-Thames. This would imply a correlation with the early members of the Kesgrave Group. However, Smith & Rose (1997) acknowledge

Authors	Location	Description of Gravels
Hill, 1908	Wilbury Hill (~TL202327)	“This gravel consists almost entirely of smallish angular and sub-angular flints and many well-rounded chalk-pebbles. Besides these, it contains pebbles of quartz and quartzites, rolled fragments of a pinkish or red rock (not Red Chalk) none of which exceed 1 ½ inches in length, and also many small pieces of ironstone. The Jurassic debris seen in the pits near Hitchin, with fossiliferous limestones, *Gryphaea* and belemnites is absent.” (Hill, 1908).
Priest, 1921	‘Tail Pit’ ~ (TL218275) ,	“Mica-schist (Scandinavian), felspar porphyry, gneiss and basalts of several varieties. Igneous rocks somewhat decomposed suggested green toadstones, diabase, and andesite. Sedimentary rocks were Red Chalk, Great Oolite with abundant shells; fine grained Oolitic rocks; green coloured micaceous sandstones; sandstones showing current-bedding, ripple-marks and plant fragments; Carboniferous sandstones, various; Millstone Grits, some very coarse with quartz pebbles ; Jurassic shelly limestones; Carboniferous limestones” [*various*]... “considered by the writer to have come from a high *Dibunophyllum* zone.” (Priest, 1921).
Priest, 1921	Ippollitts Pit ~ (TL206272),	“Jurassic shelly limestones... Red Chalk, phosphatic pellets, septaria, rolled *Gryphea*, O*strea* and *Exogyra*, broken belemnites, a small *Dactylioceras* (*Am. communis*) almost entire, quartz pebbles, Bunter quartzites, Millstone Grit-fairly spherical and basalt spheroids, both fresh and decomposed. Other igneous rocks suggested diabase, red syenite, and a sheared porphyroid. The most definite Permian rock was Magnesian Limestone, composed except for occasional grains of amorphous calcaerous material of rhombohedra of dolomite much coarser than examples from Bullwell (Notts).” (Priest, 1921). Blocks of compacted grit likely derived from Vectian sands from Woburn and Leighton Buzzard to Shefford. Probable Old Red Sandstone.
Smith & Rose, 1997	Fairfield Hospital (TL205354)*	Approx. constituents : 40 – 57% quartzites, 20% quartz, 16-20% flint. Minor Carboniferous chert, *Rhaxella* chert, schorl, ironstone, sandstone/mudstone/shale, and igneous lithologies.

Table 3.1. Gravels of the Letchworth area.

difficulties associated with the suggested route of this river, which would have been in existence in the Early Pleistocene. Taking a southeasterly course from the Midlands, it would have been captured by the Bytham River which extended its headwaters in the Middle Pleistocene. Support for the proposal was claimed by the presence of the Milton River deposits (Milton Formation) near Northampton (Smith & Rose, 1997). This was also a dipslope stream with an "apparently comparable catchment". However, as the Milton River transported only sand, it is inferred to have had a much gentler gradient. The proposed Letchworth River would have needed a far steeper gradient to provide the high energy environment required to transport the gravels of the Letchworth Formation (Boreham & Langford, 2006). Problems also exist in attempting to connect the two rivers, in that the Milton Formation at its easternmost point at Preston Deanery (Figure 3.2) lies at a roughly equivalent height to its supposed downstream equivalent at Letchworth. Belshaw *et al.* (2006) conducted a study of the history of Northamptonshire drainage from the Tertiary through to the Middle Pleistocene and found no evidence of a connection to the Letchworth River.

Smith & Rose (1997) did not consider the Letchworth Gravel to represent early Anglian glaciofluvial deposits owing to the low flint content and reported lack of chalk, Jurassic limestone and fossils. Smith (1992) however, did find such non-durable lithologies at the base of the deposit. He suggested that they once occurred throughout the gravels but were dissolved at higher levels by percolating groundwaters. Their preservation immediately above the Chalk bedrock was attributed to carbonate saturation of the groundwater. Even putting aside the lack of Jurassic debris, the flint content is considerably lower than that found in Anglian glaciofluvial outwash elsewhere within the Letchworth area. The stratigraphic position of the Letchworth Gravels, lying below Anglian (presumed MIS 12) till, would suggest the possibility of them being an early Anglian outwash, although bearing little resemblance to the Westmill Lower Gravels underlying such till to the south (Cheshire pers. comm.). A suggestion has been made that the Letchworth Formation represents glacial outwash from an earlier ice advance that was responsible for the lower tills seen to the west of the current study area, at Northampton and Milton Keynes (Boreham & Langford, 2006; Belshaw *et al.,* 2006). These are described in Section 3.14.1

as almost chalk and flint-free. The majority of deposits from this ice would have been eroded by the subsequent glacial advance, leaving only sporadic pockets of gravels and till.

As outlined in Sections 3.13.1 and 3.17 there is a possibility that the till overlying the Letchworth Formation originates from a later MIS 10 glaciation (Rose, in Clark, *et al.,* 2004). In this case these gravels may not be as old as inferred above and may, therefore, originate from late MIS 12 meltwaters. It was suggested by Rose (in Clark *et al.,* 2004) that the earlier glaciation advanced from the northwest. The latter may account for higher proportion of Midlands material and lower quantities of flint.

3.6. Glacial deposits

Amongst the early literature, numerous reports were published by the Geologists' Association of several field meetings in the north Hertfordshire and south Bedfordshire area. The resulting publications often included detailed descriptions of glacial deposits and landforms. In addition to Hill's reports of the drift-filled channels (Section 3.8.1) descriptions were given of the thickness and character of the till and local stratigraphy where temporary exposures existed.

3.6.1. Erratic Lithologies

The most obvious evidence of glaciation is the presence of erratic lithologies amongst tills and outwash gravels. These boulders and stones of sometimes extremely far-travelled lithologies captured the attention of many of the early workers and it is not surprising, therefore, that they were the focus of many early reports. In 1934 Bloom, whilst writing on the geology of the Hitchin area, commented "The astonishing variety of the far-travelled stones in its gravels and boulder clay provide a veritable museum for research by those who would study the transporting effect of ice". These reports led early workers to believe that the area was invaded at least once by an extensive ice sheet, depositing large amounts of debris in the form of outwash and till.

In the Arlesey-Letchworth area boulders, presumed to have been derived from the till, were found to include sandstone, basalts, Carboniferous Limestone, porphyritic rocks and many large flints thought to have originated in Yorkshire or

Lincolnshire (Hill ,1910). One of the more notable examples, reported near the railway at Letchworth, was a boulder, approximately 5.5 m by 1.5 m thick (of unknown breadth) was found within the till close to a local sandpit. It was identified as Spilsby Sandstone by Jukes Browne, Barrow and others (Hill, 1911).

At Heath and Reach (SP924275) approximately 2 m of sand and gravel and 9 m of till overlying Lower Greensand were reported to contain “a rich variety of erratics” listed in Table 3.2 (Bristow & Kirkaldy, 1962).

Details of erratic lithologies found in gravel pits in the Little Wymondley – Letchworth area, including those believed to be of pre-Anglian origin (Letchworth Gravels), are given in Section 3.5. Other reports of erratic lithologies found within the Hitchin channel area are provided by Hill (1914), Priest (1921), Bloom & Wooldridge (1929) and Bloom & Harper (1938), the findings of which are included in Table 3.2.

A few examples of what are believed by some workers to represent Scandinavian lithologies have been recorded by Hill (1914), Priest (1921) and Wyatt *et al.* (1988) and the presence of rhomb porphyries and larvikites found at Bedford and Hitchin are noted by Ehlers & Gibbard (1991). These are believed to have been transported to an area lying north of the current study area by Scandinavian ice during the early part of the Anglian and subsequently carried south by the later Anglian ice moving south. The presence of these within Anglian glaciogenic deposits is currently being debated (Moorlock *et al.,* 2001; Lee *et al*., 2002; Hoare *et al*., 2006).

The above suggest that a great variety of lithologies from geographically diverse locations have been brought into the study area by the ice. The information this provides can be used to determine ice flow patterns. The more fragile clasts e.g. limestone and Red Chalk were probably assimilated at source into the ice and transported directly to the study area, whilst the more resistant clasts including quartzite, basalt, etc. may have been carried by rivers such as the Bytham River (Rose (1994) (Section 3.4) into an area to the north of the study area and subsequently carried southwards by the Anglian ice. The presence of

Authors	Location	Description
Hill, 1912	In the Hitchin neighbourhood	Jurassic debris, rolled G*ryphaea*, belemnites, Carboniferous limestone, Red Chalk (sometimes containing *Belemnites minimus*), plus fragments of igneous rock (though not abundant).
Hill, 1914	Railway cutting between Broadwater and Watton	Sarsen stones, Carboniferous encrinital limestone, a fragment of decomposed chert (probably Carboniferous), older Palaeozoic chert with small quartz veins, fine grained calcareous sandstone (probably Middle Lias), deep red sandstone with white mica (probably Trias). Well rounded coarse quartz veined rock with some white mica, a quartz schorl rock, felspar schorl rock (altered granite) and others of quartzite may perhaps all be regarded as Bunter pebbles. Also a metamorphic rock (identified by Mr. George Barrow as of Scandinavian origin). Grey limestone, (probably Cornbrash), fossils from Gault and Oxford Clay.
Priest, 1921	Ippollitts Pit ~ (TL206 272),	"Jurassic shelly Limestones, Red Chalk, phosphatic pellets, septaria, rolled *Gryphea*, O*strea* and *Exogyra*, broken *Belemnites*, a small *Dactylioceras* (*Am. communis*) almost entire, quartz pebbles, Bunter quartzites, Millstone Grit-fairly spherical, and basalt spheroids, both fresh and decomposed. Other igneous rocks suggested diabase, red syenite, and a sheared porphyroid. The most definite Permian rock was Magnesian Limestone, composed except for occasional grains of amorphous calcaerous material, or rhombohedra of dolomite much coarser than examples from Bullwell (Notts)." (Priest, 1921). Blocks of compacted grit likely derived from Vectian sands from Woburn and Leighton Buzzard to Shefford. Probable Old Red Sandstone.
Bloom & Wooldridge, 1929	Vicars Grove (TL192 259)	Larvikite, olivine dolerite (spheroidal weathering) weathered granites and gneisses, mica schists, arkose and various quartzites.
Bloom, 1934	Gravel pits within 3 miles (4.8 km) of Hitchin	London Clay (basement bed with *Ditrupa plana,* septarian concretions) Hertfordshire puddingstone (Reading Beds) Red Chalk (Hunstanton/ Lincs), red flint with *Inoceramus (*Lincs), carstone (Beds or Norfolk), sundry Jurassic limestones (inc. lithologies from Northants) , Triassic sandstones (Midlands), Coal Measure sandstones, Silurian sandstone (Upper Llandovery), augite-diorite (Staffordshire), granophyre (Cheviots) , granite (Eskdale), mica-porphyrite, dacite or quartz-andesite (Cheviots), dolerite, arkose, various schists. Larvikite (Scandinavia), rhomb-porphyry (Scandinavia).
Bristow & Kirkaldy, 1962	Churchways Pit, Leighton Buzzard (SP927 286)	Mainly Jurassic and Cretaceous, but also infrequent mica schist, basalt, dolerite and granite, together with crinoidal 'rottenstones' and pebbles containing *Lithostrotion sp.* and *Camarotoechia sp.* from the Carboniferous Limestone.

Table 3.2. Examples of descriptions of gravels within the study area.

Spilsby Sandstone within the Hitchin Gap, together with Red Chalk (also found at Heath and Reach) suggests ice flow from areas of southeast Yorkshire/Lincolnshire lying between north and NNE of the study area. However, the presence of Triassic debris may indicate ice flow from the NNW. This is discussed in more detail in Chapter 9.

3.6.2. Till

Surface tills across the study area have been reported to possess certain uniform characteristics. General descriptions are of an unsorted, matrix-dominant, stony clay. Clasts usually include, in various proportions: chalk and flint, Jurassic fossils and limestones together with less common far-travelled components. A decalcified layer is often present, up to approximately 1 m thick with a colour variously described as ochreous yellow (Moorlock *et al.,* 2003), olive brown or khaki (Wyatt *et al.*,1988) or brownish grey (Shephard-Thorn *et al.,*1994). This lies above an homogeneous dark blue/grey stiff overconsolidated clay rich in chalk and flint with varying quantities of sand/silt and erratic lithologies (Hill,1914; Worssam & Taylor, 1969; Wyatt *et al.,* 1988; Aldiss, 1992a; Hopson *et al.*, 1996; Moorlock *et al.*, 2003).

Sherlock (1947) compared the tills north of the Chilterns in Hertfordshire and Buckinghamshire, where the clayey matrix is composed mainly of Jurassic materials, with those of Essex with a matrix richer in chalk. These are, respectively, the Chalky Jurassic Drift and Chalky Drift of Baden-Powell (1948). The differences are due to the bedrock over which the ice has passed, the Essex ice having passed over larger areas of Chalk, whilst tills within the study area are the product of ice passing over Jurassic rocks of Lincolnshire and Cambridgeshire. Sherlock claimed that the Chalky Jurassic Drift ice moved through the Hitchin Gap to meet up with Chalky Drift ice advancing from the east up the Vale of St Albans.

Much of the till present within the study area lies within the confines of the buried channels. These deposits are more heterogeneous, indicating a great variety of depositional and post-depositional processes, and often possess gradational boundaries with glaciofluvial and glaciolacustrine deposits. Variations in these tills are attributed by Hopson *et al.* (1996) to processes such as ablation, subaqueous sedimentation, shear stress deformation and post-depositional solifluction. The presence of melt-out and/or flow tills is also indicated by the present study (Chapter 6). Such channel fill deposits are dealt with separately in Section 3.8.4.

Outside the buried channels, the tills appear to vary greatly in thickness, possibly due to bedrock control. On the Northeastern Plateau a maximum thickness of 67 m has been reported at East Hatley (TL287506). On the North Hertfordshire Chalklands the till is much thinner and has frequently ingested Clay-with-Flints (Aldiss, 1992b).

In the western part of the study area tills are usually less than 15 m thick and often have a higher proportion of clasts found towards the base (Shephard-Thorn *et al.,* 1994). At a site a little to the west of Leighton Buzzard, the base of till is noted to contain much local clay, being often difficult to differentiate from local bedrock (Davies, 1915).

West & Donner (1956) conducted a large scale study of tills across East Anglia and the East Midlands. Whilst obtaining fabric measurements at a great number of sites, some of which lie within the study area, they recorded only very brief details of the tills examined. These include the following descriptions relevant to the current study, the fabrics being discussed further in Section 3.17.

> At **Hatley St. George** (TL286509), in an open drain, a brown/grey chalky till was noted. The same description was applied to a till examined at **St Ippollitts** (TL194258) seen beneath stratified gravel. A brown chalky till was seen to be decalcified to a depth of 20 cm, resting on Gault Clay, in a clay pit at **Meppershall** (TL157374) and at **Bedford** (TL044551), in a road cutting, a brown-blue chalky till was found above Oxford Clay.

The thickness of these deposits or the depth at which they were seen is unclear, but assuming they all lie fairly close to the surface and are not overlain by further drift deposits, all these observations conform to the general picture of homogeneous widespread surface chalky till across much of the study area.

Gibbard & Aalto (1977), during an investigation of interglacial deposits at Fishers Green, Stevenage, described the underlying till as a “light grey silty clay till containing chalk and flint pebbles”. As part of an investigation of deposits to the south of the current study area, Cheshire (1986), also included a description of a till seen at Fishers Green. A borehole (TL223258) revealed a yellowish brown chalky till, found at a height of approximately 94 m O.D. This is believed to be present beneath the organic deposits described by Gibbard & Aalto (1977) (Section 3.9.1).

3.6.3. Glaciolacustrine deposits

Evidence has been found for the formation of numerous lakes within the channel sequences. They appear to have existed in both the Hitchin and Stevenage Channels following deposition of the lower tills (the Priory and Stevenage Members respectively) and again after the final retreat of the ice from the area. They are described in detail in Chapter 8.

Sherlock (1924) speculated on large areas of water trapped between the stagnating ice and the Chiltern Hills, producing proglacial lakes along the Vale of Aylesbury. He suggested torrents of water overspilling from these lakes were responsible for the formation of the Chiltern gaps, although no explanation was offered for the formation of gaps south of the ice limit. No depositional evidence appears to have been found for such a lake. However, Sherlock did consider the Hitchin Gap represents a former river valley, widened and deepened by ice.

Extensive lacustrine deposits were found during the construction of the Biggleswade by-pass, which Horton (1970) considered were similar to deposits discovered at Northampton and near Stony Stratford (SP765388). A borehole at the latter locality described in detail by Horton *et al.* (1974) displays evidence of a large shallow lake, apparently over-run by ice on three occasions. Each retreat is marked by extensive deposition of clays, often interspersed with debris derived from floating ice. Although mention was made of laboratory descriptions of the deposits at both Biggleswade and at nearby Girtford, no reference for this work was given. More recently, similar deposits have been uncovered at Broom Quarry to the immediate west of Horton’s site. As part of on-going research, sampling is underway of a “very rich organic layer” from beneath sands and gravels. Lying immediately above the Oxford Clay, these lacustrine beds have yielded shells, freshwater molluscs (*Unio*) and plant material. Preliminary results appear to indicate that lacustrine deposits in the Biggleswade area may prove to be of more recent (post-Hoxnian) origin (C. Turner, pers. comm). Thus Horton's suggestion that the lake deposits of Biggleswade and Deanshanger may represent deposition in a single large expanse of water close to the ice front would be untenable.

In the extreme south of the study area, Wooldridge (1953) claimed that a lobe of ice entered the Mimram Valley from the northeast, impeding drainage at Codicote. Similar processes produced an ice-dammed lake at nearby Kings Walden**.**

3.7. Glacial Deformation

3.7.1. The Hitchin Gap and Chalk escarpment.

Within the vicinity of the Hitchin Gap numerous examples of glaciotectonic deformation exist. Some of these are described below.

At the northern end of the Hitchin Channel, in a small pit south of Holwell (TL166321), several examples of normal faulting in the basal sands and gravels are noted. These are possibly the result of adjustment following ice loading and unloading, or solution of underlying Chalk (Etienne, 2001). Also, in the northern part of this pit, a small section of till has been overturned towards the south as a result of an ice push (Figure 8 in Hopson, 1991).

Faulting was also observed by Salter (1866) in a quarry at Hitchin railway station, lying at the head of the Hitchin Channel. It affected both Chalk bedrock and overlying drift. At the southern end of the Channel at Vicarsgrove Pit (TL178276), step-faulting was reported in bedded glaciofluvial sands and gravels by Bloom & Wooldridge (1929). It is unclear, however, whether these were extensional or compressional features.

Although lying to the immediate east of the current study area, the glaciotectonic disturbances found in the Barkway area are important indicators as to the glaciological conditions during the ice advance across the region and so are described here.

Woodward (1903a,1903b) reported up to 1.2 m of ‘chalky boulder clay’ seen beneath the Chalk in the western face of a large pit near Barkway. He considered this to be “incontestable evidence of ice-action”. Also, a shear plane in a lime-pit north of Barkway was taken to indicate an overthrust of a mass from the north. However, at least 8 large rafts of Chalk up to 17.5 m thick in this area were recognised by Hopson (1995). They lie within a zone 1 km wide and 6 km long between Stump Cross (TL319366) and Barkway village (TL385359).

3.7.2. North of the Chalk escarpment

Other rafted material is described briefly below. Although not necessarily far-travelled, these blocks of material appeared to have been swept up, carried along with the ice and often deposited again within the till, giving an apparently anomalous stratigraphic sequence.

Whilst examining a section close to Miletree Farm at Leighton Buzzard in the western part of the study area, Kitchin & Pringle (1921) observed irregular masses of very disturbed and slickensided Gault lying within the till. This material, also found at nearby Harris’s Pit, was identified as being from a higher stratigraphic horizon than is found locally and was, therefore, presumed to have been glacially transported.

A borehole (TL223412) sunk near Edworth Church recorded a transported mass of Kimmeridge Clay. Almost 29 m thick, this was identified by its contained fossils. A kilometre further west a second borehole (TL210416) also recorded a mass of Ampthill Clay which was considered by Edmonds & Dinham (1965) to be part of the same raft. The latter comprised 20 m of clay found below 2.5 m of till and above a further 6 m of till resting on Gault. The same authors suggest this raft of material may have been transported from the vicinity of Broom. This would have entailed a journey of approximately 4 km, to a position 9 m lower in the Hatley channel (Section 3.8.5).

3.7.3. Mechanisms of deformation

The deformation structures such as faults and rafts described above are characteristic of deformation tills - also referred to as deforming bed tills, deformed till, or shear till (Benn & Evans, 1998).

Banham (1975) proposed that at the base of an ice sheet a layer of unconsolidated substrate could become subjected to the same stresses as those within the ice and therefore suffer varying degrees of deformation. Impaired drainage in an impermeable clay or chalk substrate could result in excessive porewater pressures, leading to failure along a weakened plane (décollement layer) at shallow depth. He proposed a model in which bedrock rafting occurred when an ice sheet advanced up-slope and water released at the ice front was unable to escape. If pore pressures rose sufficiently, the effective shear resistance of the upper layer of bedrock was lowered below that of the ice (Boulton & Hindmarsh, 1987). Lateral pressure exerted by the ice would then lead to failure of the bedrock at the décollement surface, facilitating the detachment and transport of a raft of substrate. However, Banham's model predicted the creation of subglacial glaciotectonic structures only where the ice was moving up-slope.

Several later theoretical studies, based on limited observational work, have centred around the 'deforming bed model' which explains subglacial deformation above unconsolidated bedrock across a wide range of conditions (Boulton & Hindmarsh, 1987; Hart *et al.,* 1990; Hart, 1995; Boulton *et al.,* 2001; Evans *et al.,* 2006). The process of deformation suggested by these authors is described briefly below.

As an ice sheet moves across unconsolidated bedrock coupling takes place between the base of the ice sheet and the underlying sediment. As in Banham's model, porewater pressures become excessive in the presence of an impermeable layer. Increased porewater pressure then results in a layer of saturated unconsolidated substrate becoming incorporated into the basal layer of ice, forming a zone of deformation. Studies on tills known to have undergone such deformation have shown this zone to comprise an upper layer of homogeneous till, below which is a compact layer consisting of a highly sheared mixture of till and bedrock. At the base of this sequence lies a layer of deformed bedrock (Hart, 1995).

Erosion occurs when high shear stresses cause the base of the deforming layer to move down into the substrate. Additional material is thus incorporated into the deforming layer. Intact fragments of unconsolidated sediment or weak rock can be incorporated as rafts within the deforming layer. According to Benn & Evans (1998), such rafts of sediment will not be disaggregated during transport if their shear strength exceeds that of the deforming material. This can be the case if the porewater pressure in the raft material is lower than that of the surrounding material.

Deposition occurs when stresses within the ice fall or the shear strength of the substrate increases, usually as a result of improved drainage. The frictional strength of the substrate rises and deposition will occur at the base of the deformation zone, i.e. the sediment is removed from the deforming layer.

Ice moving over a sandy substrate (represented in the study area by a sandy till or a bedrock of Lower Greensand) would behave differently. A higher coefficient of friction and/or higher permeability enables gravels, sands and sandy diamictons to resist deformation to a much greater extent than clays and silts (Benn & Evans, 1998). Apart from water content and composition of substrate, other factors such as thickness of the substrate and temperature at the base of the ice influence the type and intensity of deformation.

Hart *et al.* (1990) considers that this model can be applied to the Anglian ice sheets of lowland Britain. A summary of recent work regarding glaciotectonics can be found in Benn & Evans (1998).

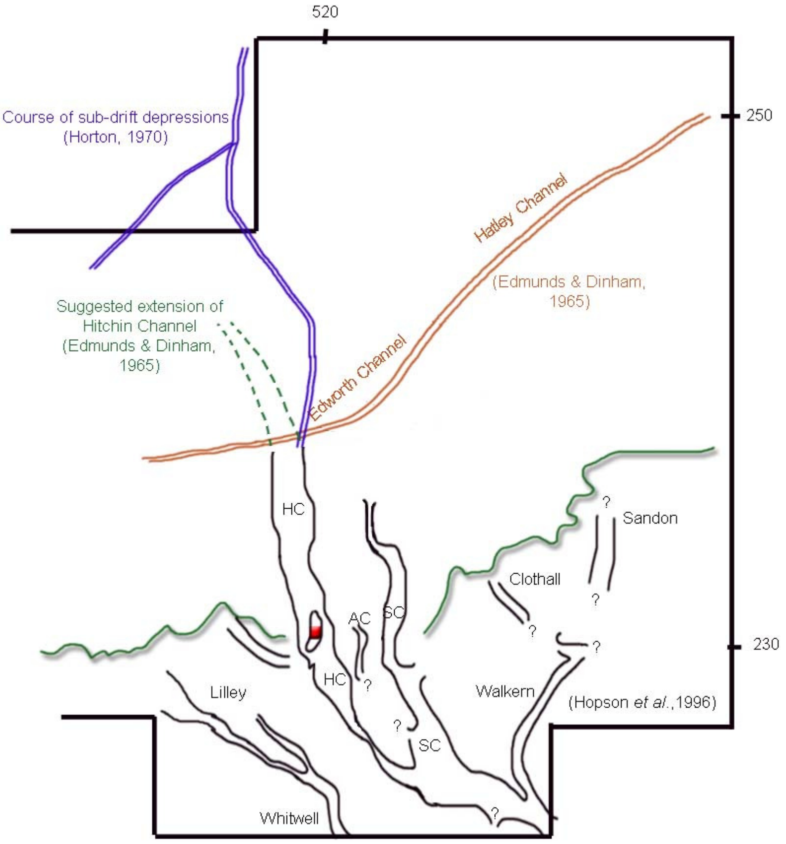
In the above examples of glacial rafting north of the Chalk escarpment, the bedrock surface comprises a soft-bed of either Gault or Ampthill Clay. To the south, the Chalk rafts at Barkway overlie the Reed Marl. In all of these examples therefore, the deforming bed model of till deposition above unconsolidated or easily eroded bedrock applies, although Hopson (1995) sought a different mechanism to account for the Chalk rafts (see below). Many of the tills deposited within the Hitchin Gap overlie older tills or lacustrine clays and silts which would also provide an impermeable substrate necessary for the deposition of deformation tills.

Hopson (1995) suggested a mechanism to account for the rafting of the Chalk near Barkway which he believed were formed as the ice front impinged upon the Chalk escarpment. He considered their existence in this specific area to be due to the alignment of the escarpment in relation to the approaching ice front. A small section of scarp of *c.*11 km is oriented in such a way as to present a barrier normal to the direction of ice movement, i.e. from the north or northeast. This would lead to higher compressional forces than experienced by the ice elsewhere. A small embayment lying approximately 2.5 km east of Royston provided access for an ice lobe, which first encountered the lower scarp topped by the Chalk Rock. The jointing, particularly well developed in the Chalk Rock of this area, would have facilitated removal of large rafts of material. These rafts were then incorporated into the leading edge of the ice and transported up-slope until reaching the major secondary scarp to the south. This scarp provided a major barrier over which the rafts could not be transported. They were therefore deposited at the foot of the scarp before the ice over-rode the escarpment completely and continued to advance south. The presence of the Reed Marl below the Chalk Rock is considered to have acted as a plane of décollement over which the rafts of broken chalk moved.

The above model of emplacement was favoured by Hopson (1995) over the model suggested by Banham (1975) described above, which he felt inadequately explained the occurrence of these rafts.

3.8. Buried channels

Numerous buried channels have been reported within and adjacent to the current study area. These are just a few of those mapped across East Anglia, thought to be a characteristic of Anglian drainage patterns (Ehlers & Gibbard, 1991). They were described by Woodland (1970), who likened them to subglacial tunnel valleys of Denmark and northern Germany (Section 3.8.6). Figure 3.4 shows the locations of channels suggested by previous workers. Horton *et al.* (1974) suggested a drift-filled channel running south from



HC - Hitchin Channel
SC - Stevenage Channel
AC - Ashbrook Channel

╱ Chalk escarpment

🟥 Hitchin

Figure 3.4. Suggested buried channels in the study area.

Huntingdon, dividing into two just north of Sandy. One channel turns west, roughly following the course of the River Ouse and one follows the River Ivel to Hitchin. The channel following the Ouse is shown by Horton to stretch as far west as Cardington. Further evidence of its continuation is lacking until the River Ouzel is reached, beyond the western boundary of the study area. A similar drift-filled channel runs in a north-south direction beneath the Ouzel Valley.

Hopson *et al.* (1996) described buried channels within the Hitchin area and conducted a detailed examination of their morphology and infill deposits, enabling them to be categorised into different channel types according to whether they were pre-existing valleys prior to the Anglian and whether they had suffered significant erosion. Of the channels shown in Figure 3.4 only the Hitchin and Ashbrook Channels are considered to represent tunnel-valleys. Other channel-types considered by Hopson *et al.* (1996) to exist in the Hitchin area include those following the course of pre-glacial valleys, e.g. the Stevenage Channel - suffering only slight glacial modification, channels tangential to the ice margin, e.g. that shown immediately west of Hitchin, and englacial channels represented by patches of sandy gravel within the till, such as those near Sandon and Clothall (Figure 3.4). A further channel between Lilley and Whitwell lies at the limit of the ice sheet and is filled with glacial deposits.

Typically these channels are filled with a complex sequence of glaciofluvial sands and gravel together with various types of till and frequent glaciolacustrine deposits. They are relatively uncompacted sediments which may have undergone considerable settling. Although Ó Cofaigh (1996) noted tills are present only rarely within tunnel valleys, borehole data and the current work shows substantial lenses, wedges and sheets of massive tills up to 30 m thick (Aldiss 1992b). However, rapid variation frequently occurs in these glacigenic sediments, tills grading into sandy or silty clays or becoming increasingly gravelly.

3.8.1. Channels within the Hitchin Gap.

Hill (1908) described the geography of the Hitchin Gap and the two valleys lying within and published the first descriptions of the buried channels. Data from five boreholes located across the Hitchin area proved the existence of a ”deep and narrow channel of drift”. These borings included those at Holwellbury, north of Hitchin, where 103 m of drift was found to overlie the Gault and at Ransom’s Brickyard in the town, where a further 104 m of drift was proved. Hill initially traced this channel for over 11 km from Holwellbury to Newton Wood, east of Langley. In a further paper, Hill (1912) described the drift-filled Stevenage Channel in more detail and described new borehole data from the ‘Bird in Hand’ at Stondon, indicating a northerly extension of the Hitchin Channel.

Brown (1959), in mapping the sub-glacial floor of the Hitchin Gap, reported what she termed a “gorge like feature" running from Hitchin to Langley. A threshold exists at Langley, marking the termination of the Hitchin Channel, although the Hitchin Valley continues south of Broadwater passing into the Stevenage Channel, which in turn runs southeast to join the Beane Valley to Watton-at-Stone and on to enter the Vale of St Albans west of Hertford. Also inferred in this work and that of Woodland (1970) is a link between the Stevenage and Hitchin channels north of Little Wymondley (TL215275). More recent studies however, have shown that this cannot be substantiated. Aldiss (1992b) reported that re-interpretation of the sub-glacial surface shows the only possible northward continuation of the Stevenage Channel to be towards Letchworth. The Stevenage Channel is shown on the current BGS 1:50,000 Sheet 221 to extend as far north as the outskirts of Letchworth.

On the BGS 1:50,000 Sheet 204, the Hitchin Channel is seen to extend as far north as Broom (TL175435). At Broom itself, surface sands and gravels are post-Anglian and the underlying extensive lacustrine deposits may also prove to be post-Anglian. The possible upstream continuation of the Hitchin Channel to the north is discussed in Section 3.8.5. It is possible that the considerable depth of lacustrine sediment here infills a pre-existing subglacial channel. A little to the northeast of Broom at Ickwell Bury, Edmonds & Dinham (1965) note a borehole at TL146460 sunk in 1952 and recording till to ~ 3 m O.D., implying the presence of a further deep channel in the bedrock. However, borehole records inspected as part of the current study show drift deposits reach a maximum thickness of 16.4 m, rather than 27 m as indicated by these authors, the Oxford Clay bedrock lying at 13 m O.D. Obviously there is some confusion regarding stratigraphy in this area, as a further borehole at Northill Rectory (TL148465) suggests the presence of ‘boulder clay’ to 9 m O.D., but a note appended to the borehole record by members of the BGS claims a re-survey found no drift deposits to be present. The superficial similarity of the clay bedrock to the clay till is likely to be the cause of this confusion.

The different characters of the two channels was noted by Culpin (1921), who remarked that the Stevenage Channel, being in places twice the width of its counterpart, possesses a shape more reminiscent of dry valleys found within the area. At the northern end of the channels, he used borehole evidence to show that the floor of the Stevenage Channel lay approximately 30 m higher than that of the Hitchin Channel. In the south, however, although the Stevenage Channel remains at approximately the same height, the Hitchin Channel lies 16 m above it. Thus the floor of the Hitchin Channel rises up steeply between Gosmore and Langley. The steepness of the channel sides was illustrated at Langley Bottom where over a horizontal distance of some 275 m the Chalk bedrock was shown to drop from the surface to a depth of 24 m below sand and gravel (Culpin, 1921).

These observations have largely been supported by more modern borehole investigations and geophysical surveys. Chacksfield & Raines (1992) suggest the floor of the Hitchin Channel lies at *c.*-20 m O.D. at TL186275 south of Hitchin, rising to *c.*55 m O.D. at Langley. These surveys also confirm the presence of a steep-sided structure. The deepest part of the Hitchin Channel so far recorded is in the Henlow district, where a boring at the “Bird in Hand” (TL164356) records drift to -52.2 m O.D. above the bedrock (Hill, 1908). Other reports are of drift deposits to -24 m O.D. in the Pollard’s Nurseries borehole (TL165349) and *c.*-20 m O.D. to the south at Ransom’s Brickyard (TL187285), although the latter borehole is believed to lie above an enclosed hollow in the channel (Hopson *et al.,* 1996). Some of these records, however, originate from the early 20th century and give only brief details of the strata, so they may be rather unreliable. Beneath the town of Hitchin itself, the buried channel is incised into the Gault bedrock, the Chalk having been eroded away. Further north near Holwellbury the floor is excavated into Woburn Sands.

Thus, the Hitchin Channel is narrower and deeper than the Stevenage Channel, having steeper sides and an irregular floor. The latter characteristics are similar to those shown in tunnel valleys of the continent (Section 3.8.6).

3.8.2. The origin & evolution of the buried channels

The exact form of the Stevenage and Hitchin Valleys prior to glaciation is uncertain. Aldiss (1992a) suggested that a south-draining river occupied the Stevenage Valley breaching the escarpment at a height of 65 m O.D. or less. However, this suggestion was based on his interpretation of the Letchworth gravels as a fluvial deposit by Smith & Rose (1997) (Section 3.5), now considered unlikely (Belshaw *et al.,* 2006). Nowell (1991) suggested a north-flowing river once ran through this valley, considering it to represent the route of the proto-Thames. However, a lack of supporting lithological evidence makes this unlikely (Cheshire, pers. comm).

It is likely that a former stream or river flowed through the Hitchin Gap, probably along the course of the present Stevenage Valley, following a general trend of dipslope left bank tributaries of the Thames prior to the Anglian Glaciation (Boreham & Langford, 2006). There is general agreement in the literature that substantial modification and enlargement of both valleys, including breakdown of the watershed and creation and infill of the channels, occurred as a result of the glaciation. The Hitchin Channel is considered for the most part to be a feature of erosion by sub-glacial waters pouring through the Hitchin Gap, the northward extension of the drift filled channel marking the route of the north-south subglacial stream. Subsequent to the initial ice advance through the Gap, this channel is thought to have become the main outlet, deeper and larger than the Stevenage Channel. Hopson *et al. (*1996) consider meltwaters first to have entered and eroded the pre-existing Stevenage Valley before advancing west over the interfluves and into the Hitchin Valley. These authors consider the threshold at Langley to mark the position of an eventual breach of a proglacial lake situated within the Hitchin Channel prior to the advance of the final Maydencroft Till ice. The formation of such a feature can be accounted for by the processes of tunnel valley formation (Section 3.8.6).

Thus, the results of these early studies, together with those of modern geophysical studies, suggest two different modes of formation of these channels. The Stevenage Channel is thought to represent the course of a preglacial valley, which was slightly modified during glaciation. The Hitchin Channel, however, was considered the creation of sub-glacial and glacial processes.

3.8.3. The Ashbrook Channel

The Ashbrook Channel, shown on Figure 3.4 is a narrow structure infilled with till, sand and gravel. Excavations on the east margin have shown it to possess steep sides with gradients of up to 1 in 8. The floor of the channel lies at approximately 56 m O.D. and is thought to be covered with a basal layer of till, though the channel fill (approximately 25m in all) consists mainly of glaciofluvial sand and gravel (Hopson *et al*., 1996). It is possible that this channel marks the route of a former tributary to the pre-Anglian river described above. However, its present physical characteristics (described above), lead to the assumption that this valley has been eroded considerably by ice and is therefore considered to have formed at the western margin of the tongue of ice pushing down the Stevenage Valley. Further subglacial erosion would have occurred as the ice sheet expanded across the interfluves to the west and into the Hitchin Valley. The outline of this channel is shown on BGS 1:50,000 Sheet 221 for a distance of less than 2 km, however Figure 24 of Hopson *et al*. (1996) suggests a course of approximately 4.5 km.

3.8.4. Channel infill

Hopson *et al*. (1996) used data from geophysical surveys conducted across the Hitchin Channel together with borehole logs from both channels, to arrive at a stratigraphical sequence. This includes a series of predominantly glaciofluvial sediments, together with six separate tills and extensive glaciolacustrine sediments, all assigned to the Lowestoft Formation. General observations within the Hitchin Channel showed that till was largely absent along the eastern side and in the deeper mid-channel sections. Woodland (1970) noted that sands and gravels were more common in the south, finer sediments such as clay and silt dominating the sequence in the north. Names were assigned to the till units but Hopson *et al.* (1996) made it clear that they did not necessarily indicate separate ice advances, merely that correlation was not possible on the basis of the limited data available. These deposits are described in more detail below, the new names assigned by Lewis (1999) being given in brackets. A summary of the stratigraphy of the Hitchin and Stevenage Channels is shown in Table 3.3 along with details of deposits seen at Holwell by Etienne (2001) (described later in this section).

Aldiss (1992a & 1992b) correlated various tills and glaciofluvial deposits within the Hitchin Gap with those of the Vale of St Albans to the south. In doing so he used the stratigraphy of Gibbard (1977). However, this stratigraphy was revised by Cheshire (1986) – as described in Section 3.12.4. Sherlock & Pocock (1924), Sherlock, (1947), Clayton & Brown (1958) and Gibbard (1974) considered that a lobe of ice travelled through the Hitchin Gap, into the Lower Beane Valley and on to the Vale of St Albans. Cheshire disputed the evidence for this, his fabrics showing an advance into the Lower Beane Valley from the northeast across the North Hertfordshire Chalklands and the ice depositing the Ware Member moving east to west along the Vale between Foxholes (TL344158) and Holwell Hyde (TL263116). This led him to conclude that the ice sheet entered the Vale of St Albans from the east rather than from the north through the Hitchin Gap.

The correlations suggested by Aldiss (1992a, 1992b) and presented in Hopson *et al.* (1996) are based on the heights and approximate stratigraphic position. In the current study, detailed analytical comparisons are made between tills within the Hitchin Gap and the Vale of St Albans/Lower Beane Valley, the results of which are discussed in Chapter 7. Thus, only brief references are made below concerning equivalence of deposits suggested by Aldiss (1992a, 1992b) and Hopson *et al*. (1996).

The basal deposits of the Stevenage Channel are described at Little Wymondley. They comprise glaciofluvial outwash, said to be laterally discontinuous, resting on Chalk at ~ 44 m O.D. Aldiss (1992b) correlated them on the basis of stratigraphic position, with the Westmill Lower Gravel of south Hertfordshire (Gibbard 1977). These sands and gravels are overlain by a grey silty chalky till, the **Stevenage Till** (Stevenage Member). This is cut out against the sides of the channel and varies from 1.4 m to over 9.0 m thick, the base of

<table>
<tr><th>Holwell Quarry Northwest Hitchin Channel (after Etienne, 2001)</th><th>Hitchin Channel (after Hopson *et al.,* 1996)</th><th>Stevenage Channel (after Hopson *et al.*, 1996)</th></tr>
<tr><td>Upper Holwell Sands</td><td>Glaciofluvial outwash & postglacial fluvial deposits</td><td>Glaciofluvial outwash and postglacial fluvial deposits</td></tr>
<tr><td rowspan="2">Holwell Diamicton</td><td>Vicarsgrove Till</td><td>Graveley Till
(Graveley Member)</td></tr>
<tr><td colspan="2">Maydencroft Till (Maydencroft Member)</td></tr>
<tr><td>Lower Holwell Sands</td><td>Glaciofluvial outwash</td><td>Glaciofluvial outwash (Westmill Upper Gravel)</td></tr>
<tr><td rowspan="4"></td><td colspan="2">Charlton Till (Charlton Member)</td></tr>
<tr><td>Glaciolacustrine (Thistley Farm Member)
subglacial fluvial deposits</td><td>Glaciolacustrine deposits (Thistley Farm Member)</td></tr>
<tr><td>Priory Till
(Priory Member)</td><td>Stevenage Till
(Stevenage Member)</td></tr>
<tr><td>Glaciofluvial outwash and subglacial fluvial deposits</td><td>Glaciofluvial outwash</td></tr>
</table>

Table 3.3. Stratigraphic relationships within the Hitchin Channel.

(Names in brackets after Lewis, 1999).

which is reported to fall to approximately 55m O.D.

The lowermost till of the Hitchin Channel overlies the subglacial fluvial deposits in the centre of the channel and the Chalk at the channel margins. Named the **Priory Till** (Priory Member) by Aldiss (1992b), this lies between 31 m and 32.5 m O.D. in the Gosmore borehole (TL186275) where it is described as a sandy lodgement till. At Ransom's Brickyard (TL187285) Hopson *et al.* (1996) showed this till to continue to a depth of 23.2 m O.D. They report it to exist only at the northern end of the Hitchin Channel, having been completely eroded away in the south. Aldiss (1992a, 1992b) considered both the Stevenage Till and the Priory Till to be the equivalent of the Ware Member till of the Vale of St Albans (Gibbard, 1977).

The Priory Till is overlain by a considerable thickness of glaciofluvial sands and gravels (Gosmore Member), reaching over 12 m in the Gosmore Borehole where they are shown to be cyclic, generally becoming finer with depth. Fragments of fossilised wood in this deposit are believed to have originated in the Woburn Sands 4 km to the north. This led Hopson *et al.* (1996) to suggest that much of the sand in the Gosmore Member was re-worked from the underlying Lower Greensand. There does not appear to be a similar deposit overlying the Stevenage Till in the Stevenage Channel.

A thick sequence of glaciolacustrine sediments (Thistley Farm Member) interspersed with the waterlain **Charlton Till** (Charlton Member) is found in both the Hitchin and Stevenage Channels. These overlie the Gosmore Member and the Stevenage Till respectively. Gravity surveys have suggested that the Charlton Till reaches thicknesses in excess of 30 m to the west of Hitchin (Chacksfield & Raines, 1992), where it outcrops along the Hiz Valley. It is composed of various pebbly, sandy or silty clays, clayey or sandy silts and lies within glaciolacustrine thinly bedded, sometimes laminated silts, sands and clays with dropstones and till intraclasts, in places faulted and slumped. The surface of this till has been eroded and in places is overlain by glaciofluvial sands (Aldiss, 1992a; 1992b). The top of this sequence lies at ~70 m O.D. within the Hitchin Channel and between 65 and 85 m O.D. north and northwest of Little Wymondley in the Stevenage Channel. Aldiss (1992a) suggests that although proglacial lakes were present in both channels at this time, it is probable that no connection existed between the two. These glaciolacustrine deposits do not occur within the Ashbrook Channel.

A further ice advance is then indicated by the presence of proglacial outwash deposits seen in both Stevenage and Hitchin Channels. These have been correlated by Aldiss (1992a; 1992b) on the basis of their stratigraphic position above the lowest till, with the Westmill Upper Gravels (Hertford Member) above the Ware Member of Gibbard (1977). At Broad Meadow (TL193277) these deposits appear to have been laid down on an erosion surface.

This ice advance is represented by the **Maydencroft Till**, the typesite of which is at Maydencroft Manor (TL1829 2760). This firm, dark grey chalky till, sometimes with a sandy base, rarely exceeds 10 m in thickness and is interpreted as a lodgement till by Hopson *et al.* (1996).

On the basis of its stratigraphic position as a surface till in the Hitchin area, the Maydencroft Till is correlated by Aldiss (1992a; 1992b) with surface tills across the wider area and is equated with Gibbard's Eastend Green Member till (Gibbard, 1977). The latter till was reported by Gibbard to exist throughout the Vale of St Albans, deposited by ice moving southwest from Hertford to Moor Mill where, he claimed, it dammed the proto-Thames. It should be noted however, that as will be explained in Section 3.12.4, Cheshire (1986) found Gibbard's Eastend Green Till included parts of the Ware Till in the southwest of the Vale of St Albans and Lower Beane Valley. The Ware Till was deposited by the initial ice advance into the Vale of St Albans. Thus, Cheshire considered the Ware Member till the most extensive, reaching into the Hitchin and Stevenage Valleys and the ice which deposited it was instrumental in diverting the proto-Thames from the Vale into the modern Lower Thames valley through London. A small area to the southwest of the study area remained clear of ice, as indicated by the presence of an ice marginal lake near Whitwell (Hopson *et al.,* 1996).

The presence of more localised tills, interpreted as waterlain/flow tills at Vicarsgrove and Graveley are interpreted by Aldiss (1992a) as indicating the presence of further proglacial lakes, following the decay of the Maydencroft Till ice. The **Vicarsgrove Till** was described by Aldiss (1992a) as a greyish brown very chalky till with a thin layer of gravelly sand at the base which outcrops in the area of the old Vicarsgrove gravel pit (TL192259) now used as a landfill site. It thins out towards the west and south and passes into glaciolacustrine deposits to the east. According to Lewis (1999) the Vicarsgrove Member comprises a 3.5 m thick layer of sand which presumably forms part of the same sequence.

The **Graveley Till** (Graveley Member) was described in boreholes west of Graveley along the line of the A1(M). In part laminated, this gravelly, sandy silty clay with chalk and flint gravel reaches almost 17 m thickness, the base lying above 95 m O.D (Aldiss, 1992b).

Further glaciolacustrine deposits are found above the Vicarsgrove Till in the Hitchin Channel and the Graveley Till in the Stevenage Channel. These waterlain/flow tills are the highest in the channel sequences and are believed to have been deposited in proglacial or periglacial lakes (Hopson *et al.*, 1996). Culpin (1921) was able to trace most of the border of the lake within the Stevenage Channel, which he believed to be 3.2 km long and 1.6 km wide, at an approximate height of 97 m O.D. Deposits that presumably relate to this lake were sampled at Fisher's Green (TL224260) and described by Gibbard & Aalto (1977).

At Holwell Quarry (also known as Primrose Hill Quarry – Site 11, this study) on the western side of the Hitchin Channel north of Hitchin, Etienne (2001) established a stratigraphy. Although detailed sedimentological and palaeontological descriptions of the deposits were made, no attempt was made to compare them to those within the Vale of St Albans. Rather, correlations were based on the brief descriptions and approximate stratigraphic relationships proposed by Aldiss (1992a & 1992b) (Table 3.3). Thus, the Holwell Diamicton was equated to the highest tills in the Hitchin Channel (Maydencroft/Vicarsgrove Tills) and the highest till in the Vale of St Albans - the Eastend Green Till of Gibbard, (1977). Below this till, the Lower Holwell Sands were equated with the gravels lying below the Eastend Green Till – the Westmill Upper Gravel. The presence of the proglacial lake suggested by Hopson *et al.* (1996) to occupy the channel between Holwell and Langley, may imply that the sequence described by Etienne is somewhat different from that found at Hitchin, making correlation of deposits more difficult. It is of interest to compare this to the borehole at 'The Bird In Hand' at Henlow where Hill (1912) reported *c.*108 m of drift. The latter gives some indication of the depth and complexity of the glacial deposits at this location.

Comparisons of textural, lithological and macrofabric data from tills at this quarry carried out as part of the current study are discussed in Chapters 6 & 7.

3.8.5. Other drift-filled channels

Deep drift-filled channels have also been identified extending from Biggleswade to Huntingdon, beyond the northern margin of the study area. These appear to take the form of a series of deep depressions at intervals of three to four miles along the valleys of the rivers Ivel and Ouse (Horton, 1970). It may be that these channels are related to that forming the northern extension of the Hitchin Channel shown on the BGS 1:50,000 Sheet 204 (Biggleswade). Horton (1970), however, was convinced that they follow the course of the present Ouse Valley, linking with extensive lacustrine deposits at Deanshanger (SP765388) beyond the western margin of the study area.

To the west of the River Ivel, Page (1904) noted the presence of a "great pre-glacial valley" roughly centred on Northill (TL148465) and pre-dating that of the Ouse. It was suggested that it may have represented the course of a large river, or "the deep channel of a glacier". Over 30 m of glacial deposits within this valley were envisaged at the time. More recent data confirms that at Ickwell Bury (TL146460) *c.*16.5 m of gravel, sand and till overlies the Oxford clay. This may mark the position of a further northern extension of the Hitchin Channel.

The northernmost part of the Hitchin Channel shown on the BGS 1:50,000 Sheet 221 near Langford (TL185405), crosses that of another deep channel described by Edmonds & Dinham (1965). The Hatley Channel is claimed to be up to 45 m deep and perhaps 19 km long, stretching from East Hatley (TL284509) to Woodbarn (TL355571). This channel appears to extend a little further to the east, where Boreham (2002) reported up to 26 m of chalky diamict (Toft Diamict) resting on Chalk at 17 m O.D. near Toft (TL359562). A little further to the north at Hardwick (TL372594) the bedrock was seen to rise to 39 m O.D. A continuation of the Hatley Channel is shown by Edmonds & Dinham (1965, Figure 5) as the Edworth Channel extending southwestwards from East Hatley, passing south of Langford and on to Shefford where it appears to coincide with the course of the Flit Valley. A sub-glacial contour map produced by Sparks (1957) shows a strike-oriented channel in the centre of which lies a small depression descending to below 50 m O.D., above a Lower Greensand inlier. Sparks was of the opinion that this could have been the result of scouring by ice or subglacial waters. Edmonds & Dinham (1965) consider a pre-glacial northeasterly flowing river (the Edworth River) occupied this channel, possibly fed by the ancestors of the Flit and Ivel, subsequently deepened during glaciation. This is shown in a cross section on the BGS 1:50,000 Sheet 204 published in 1976, reproduced in part in Figure 3.5.

Evidence of further buried channels has been found beneath the upper reaches of the Cam-Stort Valley, lying to the east of the current study area (Sparks & West, 1965). This channel system is similar to that found at Hitchin (Woodland, 1970), and Lake & Wilson (1990) believe the two systems could have been created at the same time and by the same processes.

Other smaller-scale structures are mentioned in the literature, including channels found at the base of till in sand-pits around Heath and Reach (Shephard-Thorn *et al.,* 1994). In particular a WNW-ESE trending channel 50 m wide, of unspecified depth, is recorded at Stone Lane Quarry, Heath & Reach (SP931291) (Site 30 of the current study). A photograph of this structure appears in Moorlock *et al*., 2003 *(*plate 10, p. 89*).* At the time of writing this feature cannot be seen and presumably has been removed along with the overburden.

Shephard-Thorn *et al.* (1994) also remarked on evidence of a further pre-glacial gap and small channel in the Chalk escarpment extending from the summit of Sharpenhoe Clappers through east Luton to Luton Hoo, the course being marked by a narrow belt of sand and gravel. A similar line of glaciofluvial deposits and till lies a little to the east, stretching from the scarp summit to Lilley Bottom, crossing the margin of the area represented on the BGS 1:50,000 Sheet 220 (Leighton Buzzard) and Sheet 221 (Hitchin). The southeastern-most point

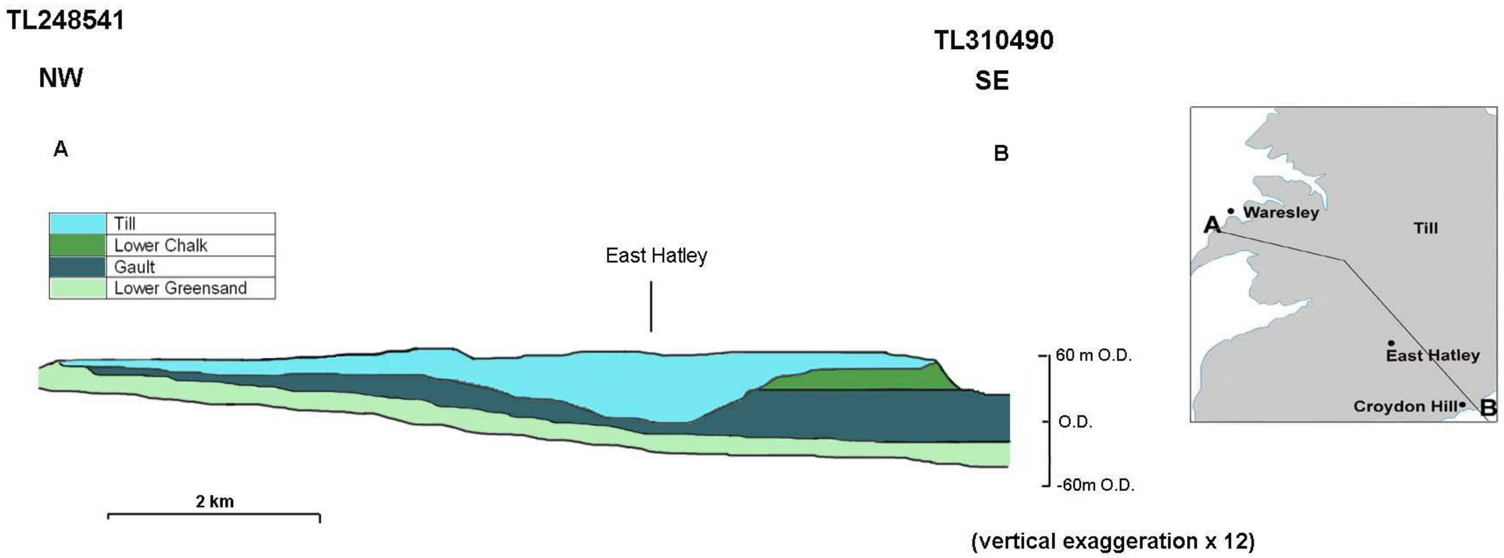


Figure 3.5. Section across the Northeastern Plateau.

(adapted from BGS 1:50,000 Sheet 204 (Biggleswade) dated 1976).

of this string of outcrops extends into, but may not be related to, a buried channel marked on Sheet 221. It is presumed that glacial drift at the northern extremities of these channels has been eroded away.

To the immediate southwest of Leighton Buzzard, Lamplugh (1915) visited Rockley Hill sandpits where a channel in the Lower Greensand, more than 6 m deep, was infilled with “bluish boulder clay”. It was noted to contain chalk, flint, basalt and oolitic debris, as well as striated blocks of Carboniferous Limestone. He considered the narrowness and steep sides of this valley to be “remarkable features in such incoherent material as the Lower Greensand”.

3.8.6. Tunnel valley formation

Early speculation as to the mode of formation of the Hitchin Channel came in a published discussion following Hill’s 1908 paper. Clement Reid suggested the possibility that the Hitchin Channel was an erosional feature cut by sub-glacial meltwater, although Salter and Kennard considered the formation of the deep channel by earth movements causing the existing valley to be filled by debris. In response Hill pointed to the presence of striated boulders within the drift and quoted the great thickness of drift discovered between Biggleswade and Sandy, possibly marking the extension of the Hitchin Channel.

Bloom (1934) realised that if the two valleys which now mark the route of Stevenage and Hitchin Channels were present prior to the Anglian ice advance, they had been substantially deepened during the glaciation. Various mechanisms by which this occurred have been proposed. If, however, only the Stevenage Channel was present in pre-Anglian times, it is necessary to account for the formation and infill of the Hitchin Channel during the Anglian Glaciation.

The western (Hitchin) buried channel, in common with others found across East Anglia, is very similar in character to those found across northwest Europe. They are typically up to 100 km long and often more than 200 m deep with ‘trough and sill’ type long profiles, incorporating reversed gradients (Woodland, 1970; Ó Cofaigh, 1996). Although Ó Cofaigh (1996) claims these valleys to be typically between 2 and 4 km wide, the BGS Sheet 221 (Hitchin) shows the Hitchin Channel to range between approximately 0.5 km and 2.5 km. Thus, it is similar to the Danish examples which vary in width between 0.5 and 5 km (Jørgensen & Sandersen, 2005). It is believed that they were all formed during the Anglian (Elsterian) glaciation, either during advance or retreat of the ice sheet (Woodland, 1970; Ehlers & Linke, 1989; van Dijke & Veldkamp, 1996). Tunnel valleys are also found in North America associated with the Laurentide ice sheet, where a good deal of research on the mechanism of formation has been conducted (Mooers, 1989; Mullins & Hinchey, 1989; Shaw & Gilbert, 1990; Patterson, 1994; Beaney, 2002).

With the exception of a study by Cox (1985), who claimed that the tunnel valleys of Norfolk were the result of fluvial erosion little influenced by glacial processes, there is a wide acceptance in the literature that erosion by subglacial water is either wholly or partly responsible for the creation of tunnel valleys (Woodland, 1970; Piotrowski, 1997; Huuse & Lykke-Anderson, 2000; Jørgensen & Sandersen, 2005).

Woodland (1970) suggested an outline of the process but gave little detail. His Figure 3 showed subglacial stream erosion occurring close to the ice front during ice melt and the subsequent infill of the channel immediately in front of the ice margin. The existence of a closed hydrological system operating beneath the ice is considered necessary to produce trough and sill profiles within the deep narrow valleys, similar to that first described at Hitchin by Hill (1912) and Culpin (1921).

Over the last decade a number of workers have undertaken high resolution seismic and geophysical studies of tunnel valley infills (Mullins & Hinchey, 1989; Huuse & Lykke-Anderson, 2000; Kluiving *et al.*, 2003), whilst others have attempted to model the glaciohydrological conditions that existed in order to explain the characteristics of these narrow deep channels (Walder & Fowler, 1994; van Dijke & Veldkamp, 1996; Piotrowski, 1997). Various mechanisms have been proposed to explain the genesis of subglacial streams and consequent tunnel erosion. These roughly fall into two groups – the first involving “steady state” processes whereby the tunnel valley is excavated over time (Mooers, 1989; Mullins & Hinchey, 1989; Kluiving *et al.*, 2003). A subglacial conduit is formed when the quantity of meltwater cannot be accommodated by Darcian groundwater flow, the presence of these conduits being necessary to maintain glacier stability (Benn & Evans, 1998; van Dijke & Veldkamp, 1996; Piotrowski, 1997). Deformable sediments forming the sides and base of the conduit become weak and undergo creep; they fall into the conduit and are washed away by fast flowing meltwater (Boulton & Hindmarsh, 1987). In this way the conduit is progressively widened and deepened forming a tunnel valley. Evidence of this process would be provided by the presence of deformation tills in association with tunnel valleys (Benn & Evans, 1998). Lack of this supporting field evidence was noted by Ó Cofaigh (1996) who quoted the work of Walder & Fowler (1994) suggesting these conditions would lead to the formation of a series of wide shallow channels rather than deep steep-sided tunnel valleys.

Huuse & Lykke-Anderson (2000) claim that requirements for the generation of tunnel valleys are poorly consolidated sediments underlying a melting ice sheet, such as existed north of the Hitchin Gap, the sediments being more readily eroded than the ice. Woodland (1970) also considered the consolidated but easily eroded chalk a pre-requisite for the formation of tunnel valleys of East Anglia. However, similar features are incised into hard bedrock in North America (Beaney, 2002; Patterson, 1994; Mullins & Hinchey, 1989).

A more convincing theoretical model was produced by van Dijke & Veldkamp, (1996). Erosion of the channels themselves would only occur at times of glaciohydrological instability, essentially on a seasonal basis. During the winter the channels would be infilled by sediment creep and ice flow. At the beginning of each melt season, supraglacial meltwater would flow towards the channels and create increased water pressure, eroding the subglacial channel bed. Re-creation of stable hydrological conditions only occurred when the rate of subglacial erosion was sufficient to compensate for the supply of supraglacial meltwater. However, during deglaciation quantities of meltwater would be too high for channel infilling to occur even in the presence of thick permeable bedrock, causing downcutting, sliding/slumping and the creation of tunnel valleys. The progressively higher rates of meltwater production during deglaciation were needed to prevent the return of stable conditions. This would imply that the geomorphology of tunnel valleys can be related to the available quantities of meltwater and therefore the climatic conditions that existed at the time of the Anglian deglaciation. The presence of thresholds within the floor of the tunnel valley (such as that suggested to exist near Langley within the Hitchin channel – see Chapter 8) is taken to indicate the presence of a stable ice sheet margin with a pause or temporary decrease in the rate of meltwater production, rather than a change in bedrock characteristics. In general this work leads to the conclusion that these tunnel valleys were excavated at a time of relatively rapid rising temperatures during the Anglian deglaciation.

In contrast, Woodland (1970) felt that the amount of debris carried by the subglacial meltwater was important in dictating the channel geomorphology. He ascribed the differences between the Danish and East Anglian structures to the lack of debris in meltwaters eroding the Danish tunnel valleys, a higher debris load enabling incision to a greater depth in East Anglia. However, he also noted differences in the bedrock of the two systems. Woodland also proposed that the tunnel valleys of East Anglia were created during *in situ* melting of the ice. He claimed "The conclusion seems inescapable that the ice advanced to a maximum then became separated from its source and died *in situ* as a great mass of stagnant ice. It was during this phase of melting *in situ* that the tunnel valley system of northeast Hertfordshire, northern Essex, Suffolk and most of west Norfolk, developed". Woodland felt this to be indicated by the lack of evidence of retreat of the ice, i.e. terminal moraine. However, this is not a view that has been forwarded by any other author and is not easily reconciled with the process of subglacial tunnel excavation.

The second group of mechanisms invoke the catastrophic release of meltwater. Here, the simultaneous formation of a whole tunnel valley system is predicted, instigated by a sudden single release, or a series of sudden torrential outbursts of subglacially stored meltwater (Ehlers & Linke, 1989; Ó Cofaigh, 1996; Jørgensen & Sandersen, 2005). Most of the work concerning this mechanism of tunnel valley formation has been focused on features of the Laurentide ice sheet, where massive outbursts of subglacially stored meltwater (jökulhaups) are thought to have occurred (Mooers, 1989; Mullins & Hinchey, 1989; Shaw & Gilbert, 1990; Patterson, 1994; Beaney, 2002). However, Ehlers & Linke (1989) used this mechanism to account for the formation of German tunnel valleys during rapid de-glaciation. Their conclusions were based on geophysical analysis of the valley infill, which were taken to indicate a series of catastrophic meltwater releases. The suggestion that depositional processes operating within the channels should also be indicative of channel formation processes is questioned by Ó Cofaigh (1996). Jørgensen & Sandersen (2005) considered Danish tunnel valleys to be the product of several glaciations, their incision due to a series of relatively small outbursts of meltwater stored in subglacial basins. In addition, direct glacial erosion, i.e. quarrying and abrasion, is considered by these authors to be an important contributor to tunnel erosion.

Many authors agree that in reality, a combination of processes is likely to be responsible and it is not necessarily the case that all tunnel valleys are formed in the same way (Ó Cofaigh, 1996; van Dijke & Veldkamp, 1996; Benn & Evans, 1998; Huuse & Lykke-Anderson, 2000). It seems, therefore, that future work may shed further light on the details of the mode of formation of the Hitchin Channel, but it remains clear that erosion by subglacial waters under hydrostatic load close to the ice front is very likely to be responsible for carving out at least part of this channel. The excavation of the deepest known part of the Hitchin Channel at Henlow, to a depth of more than 108 m, would appear to require very powerful glaciofluvial action, whether in a sudden outburst or over a length of time. The presence of a subglacial channel at Hitchin suggests a very considerable quantity of meltwater was produced at a time when a sufficient thickness of ice existed to create the hydrostatic pressure required for subglacial erosion. This channel, the floor of which rises to the south, was subsequently infilled with glaciofluvial deposits and tills.

The pre-Anglian presence of a weakness in the chalk scarp at Hitchin (perhaps in the form of a through-valley in the chalk cuesta) determined the path of the Hitchin tunnel valley, i.e the subglacial hydrology was determined by the pre-existing relief. The Hitchin Channel is one of several arranged radial to the Anglian ice margin across East Anglia (Woodland, 1970).

3.9. Post-Anglian interglacial deposits

Hoxnian interglacial deposits directly overlie till at the typesite in Suffolk and at several locations within and adjacent to, the study area. Following Mitchell *et al.*

(1973) the till has been assigned to the Anglian, correlated with MIS 12 (Bowen *et al.*, 1986). The inference is that at these sites the Hoxnian deposits relate to MIS 11. This view was challenged by Bowen (1999) on the basis of amino-acid dating of shell material from the interglacial deposits at Hoxne to MIS 9. However, the MIS 12 – 11 relationship is confirmed at sites such as Swanscombe and Clacton-on-Sea where typical Hoxnian vertebrates occur in deposits that immediately post-date Anglian fluvial deposits (Schreve, 2001). In particular some evidence of weathering or pedogenesis might be expected during MIS 11 and 10 if an MIS 9 date is postulated, but this has not been observed at these sites. Deposits of this interglacial, therefore, form important marker beds throughout eastern England.

The following is a summary of sites of considered to be of Hoxnian age in the region of the study area, together with the implied stratigraphy in each case.

Hopson *et al.* (1996) have suggested that remnants of the Hoxnian land surface extend along the higher ground within the Hitchin Gap, between Fishers Green at Stevenage and the Oughton Valley on the outskirts of Hitchin. The following is a summary of sites found there.

3.9.1. Hitchin Formation

Deposits in south Hitchin were recorded in detail by Reid (1897) and a further comprehensive investigation of these sediments was carried out by Boreham & Gibbard (1995). Two boreholes, 300 m apart, close to Gosmore proved dark often fossiliferous clays beneath variable post-Hoxnian brickearths known locally to contain Palaeolithic artefacts. Pollen assemblages from these clays indicated a transition from a shallow pool environment during a late glacial/early interglacial period to coniferous woodland. This now represents the stratotype of the Hitchin Formation (Lewis, 1999). Both boreholes recorded a typical chalk-rich sandy basal till believed to be of Anglian age.

The discovery of a tufa deposit led Kerney (1959) to investigate the stratigraphy in the lower Oughton Valley northwest of Hitchin. At the time of this research, it was considered that both Anglian and Gipping glacial deposits could be recognised. The Anglian was represented by sandy outwash gravels containing glacial erratics directly overlying the Chalk bedrock. Above these gravels lay a brickearth, containing mollusca indicating full interglacial conditions, followed by a gradual transition into the overlying tufa. Unconformably overlying the last was a meltwater gravel, mainly composed of sub-angular flints, red and white Chalk, Carstone, vein quartz and abundant Jurassic *Ostrea* and belemnites. Kerney (1959) believed the uppermost part of the sequence represented the Gipping glaciation which it was considered left "abundant local traces”. However, Hopson *et al.* (1996) notes that this deposit is now regarded as Devensian head.

In 1974, during construction of an underpass at Fishers Green (TL224260) 2 km NNW of Stevenage, a series of interglacial clays and organic muds were found overlying chalky till. The latter formed part of a considerable depth of glacial deposits within the Stevenage Channel (Gibbard & Aalto, 1977). The pollen sequence was determined to be similar to that found at Hatfield Polytechnic (TL212075) (Sparks *et al.*, 1969) and in shorter sequences found at Bell Lane (TL183031) (Gibbard, 1974; 1977), Stanborough (TL182276) (Sparks *et al.,* 1969) and Hitchin (TL182276) (Boreham & Gibbard, 1995). Aldiss (1992a) also mentioned further interglacial deposits at Todds Green (TL219269), Coreys Mill (TL225265), Graveley (TL227281), Gunnels Wood Road (TL227255) and at Old Stevenage (TL232250). A Hoxnian age is indicated by pollen analysis at the Todds Green site and the remaining sites are also considered to be probably Hoxnian. The deposits at Todds Green and Coreys Mill lie directly above glacial sands, gravel and weathered and unweathered till respectively.

3.9.2. Hatfield Member

Hoxnian deposits were described by Sparks *et al.* (1969) at Hatfield, lying *c.*11 km south of the current study area. Lying between tills believed to represent the Lowestoft (earlier) and Gipping (later) Glaciations, the Hatfield Member was designated as MIS 9 deposits by Bowen (1999) on the basis of their similarity to the stratotype deposits at Hoxne, indicated by amino-acid ratios. Sumbler (1995) expressed his opinion that the underlying tills may therefore originate from MIS 10. These deposits however have been re-assigned on the basis of mammalian data to MIS 11 (Schreve, 2001) (see Section 3.9 above).

The distribution of Hoxnian deposits within the study area requires explanation. The sites all lie within the Hitchin Gap with the exception of Hatfield which lies to the south, within the Vale of St Albans. North of the Chalk, only post-Hoxnian fossiliferous deposits have been described. It may be that a younger ice sheet advanced across this area, terminating at the Chalk scarp (Rose, in Clark *et al.,* 2004). Organic deposits laid down during the Hoxnian may thus have been overridden and eroded during this advance, explaining why they are not known here but occur commonly to the south.

3.9.3. Post-Hoxnian fossiliferous deposits

More recent organic deposits have been recorded within the district. The study of these lies outside the current area of research, but the stratigraphical implications of these are summarised below.

Middle Devensian deposits have been discovered within the Ivel Valley just south of Sandy (Gao *et al.*,1998). These occur within first terrace gravels directly overlying a layer of soft grey sand which, the authors note, could relate to similar lacustrine deposits recorded in the Biggleswade area by Horton (1970).

On the eastern margin of the area considered in this study, interglacial sediments at Barrington have been the subject of numerous reports. The Barrington Member comprises a marl, loam sand and gravel preserved in a terrace of the river Cam. They have been found to contain mammalian fossils that are believed to originate in the Ipswichian (Lewis, 1999; Boreham, 2002) although an earlier age has been proposed (Norris, 1962). These deposits are found in close proximity to till units - further details are found in Section 3.15.1.

Organic sediments found beside the River Ivel at Broom have yet to be investigated, but a preliminary investigation shows these also to be post-Hoxnian (Turner, pers. comm).

3.10. Summary

The main results of Part 1 of this desk study are summarised below:

1. No evidence exists of a pre-Anglian glaciation in the study area.

2. A sub-glacial channel, up to 108 m deep, extends north from Langley (TL224225) to at least as far as Broom (TL175435). A further channel lying to the east and passing through Stevenage, more clearly represents the course of a pre-existing river which was further eroded under the ice. These channels contain thick bodies of glacial and glaciofluvial deposits.

3. The eroded Chalk scarp and deepened/sub-glacially eroded channels, together with the presence of rafted material and deformation structures, led to the suggestion that at least one very powerful ice advance entered the area, with large amounts of meltwater passing through the Hitchin Gap.

4. North of Hitchin large areas of till are found ranging from thin deposits (less than 1 m thick in places) on the North Hertfordshire Chalklands to thicknesses up to 67 m on the Northeastern Plateau.

5. Records of erratic lithologies contained within the till indicate that ice moved into the area from directions ranging from NNW to NNE, although not necessarily entrained from outcrop to site of deposition in a single transport path.

In order to achieve objectives 3 - 5 (Section 1.1), clarification is required regarding the number, extent and direction of each ice advance. To this end, this study attempts to seek answers to the following:

a) Is it possible to separate tills from individual advances on the basis of textural and lithological characteristics ? If so, the number of ice advances (or re-advances) into the area and the extent of each advance may be identified.

b) Using macrofabric analyses, is it possible to identify the flow paths of these advances, therefore confirming or otherwise the directions suggested in 5 above ?

CHAPTER 3

DESK STUDY:
REVIEW OF LITERATURE AND PREVIOUS RESEARCH

Part 2: Surrounding Regions

3.11. Introduction

This section includes an assessment of the literature relating to the Quaternary geology of neighbouring areas. The latter is necessary in order to put the current study into context and to provide an insight into possible correlation with deposits further afield.

3.12. South Hertfordshire - Tills of the Lower Beane Valley & the Vale of St Albans

It is likely that the speed and direction of the ice sheet advancing into eastern England may have been interrupted and altered as it impinged on the Chalk scarp. Therefore, findings in south and southeast Hertfordshire would shed light on the path of ice across/around the study area. Further, comparison of data from this study with that of Cheshire (1983a, 1986) will enable correlation of tills across the southern part of the study area and south Hertfordshire.

Many studies have been conducted on Middle Pleistocene deposits lying to the southeast (Essex) and the south (Vale of St Albans) including the Thames terraces, due at least in part to the many exposures made available by extensive gravel workings in these areas. In particular the work of Gibbard (1974, 1977, 1978a, 1978b, 1983), Cheshire (1981, 1983a, 1983b, 1986), Rose (1983), Bridgland (1994) and Cheshire & Bridgland (1994), determined the course of the proto-Thames and its diversion away from the Vale of St Albans to a new route to the south.

The units discussed in this section are, for ease of reference, given their original names. The revised nomenclature of the Geological Society (Bowen, 1999) is shown in Table 3.4.

Original names	Revised names
Westmill Upper Gravels	Hertford Member
Westmill Till	Wadesmill Member
Ugley Till	Ugley Member
Eastend Green Till	Eastend Green Member
Stortford Till	Stortford Member
Ware Till	Ware Member
Watton Road Silts	Watton Road Member
Westmill Lower Gravels	Westmill Member

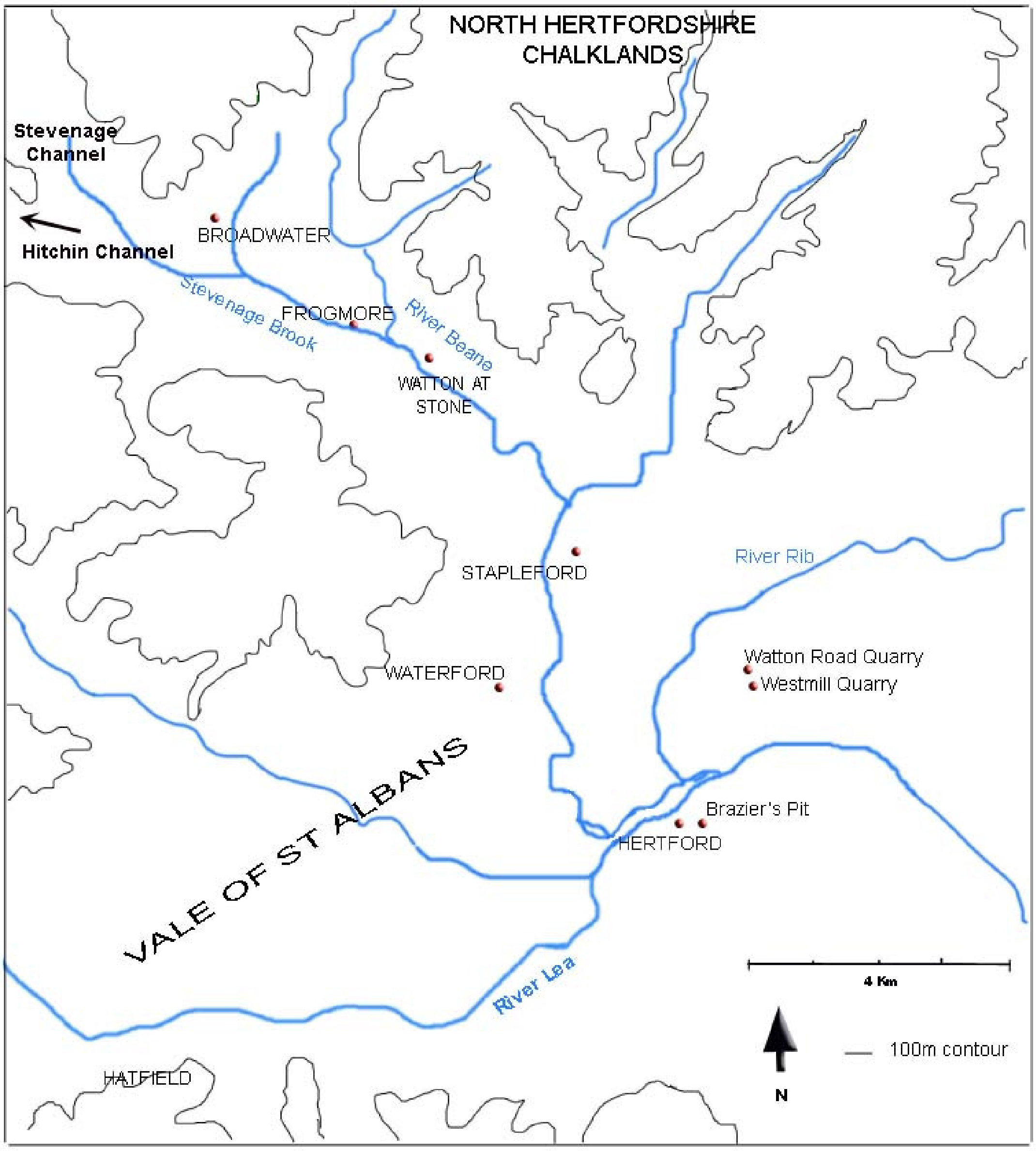
Table 3.4. Revised nomenclature of deposits in the Vale of St Albans & Hertfordshire referred to in the text (after Bowen, 1999).

The sequence of glacial deposits in this area is complex, with evidence of multiple ice advances. Sherlock (1924) recorded two tills in the vicinity of Ware, interspersed with sands and gravels and laminated clays. Sherlock & Pocock (1924) believed that the two ice sheets approached the area from different directions.

3.12.1. Hill (1914)

One of the first detailed reports of the tills in this area was made by Hill in 1914. During construction of the Stevenage to Hertford railway, an excursion by the Geologists' Association was arranged to examine new exposures. Strata observed at Broadwater (now part of southern Stevenage – Figure 3.6) included 3.5 m of clay lying above gravel. The lower two thirds of the clay was described as grey-blue till but the upper third was described as brownish grey clay with no chalk (presumably decalcified).

Towards Watton-at-Stone the underlying gravels passed into current-bedded sands and gravels. Hill remarked on the scarcity of clasts within the till between Watton and Broadwater, describing it as containing "comparatively few small chalk pebbles or flints, or any other boulders". He did however, identify a number of erratic rocks found here including fossiliferous rocks from the Upper and Middle Jurassic. Till at Watton-at-Stone was noted to contain lenses (up to 18 m long) of sandy silt.



(100 m contour shown).

Figure 3.6. The Vale of St Albans and localities mentioned in text.

At the site of Hertford North Railway Station, blue-grey till passing into an upper decalcified layer, was noted to be almost free of clasts, with only a few small chalk fragments visible. This latter was overlain by 7.5 m of sand and gravel, presumably representing the Westmill Upper Gravels.

3.12.2. Clayton & Brown (1958)

Investigations of several pits in the Waterford area revealed a succession of three tills and intervening bedded sand and gravels. The lowest of these was described as a dark blue tough chalky till lying between 52 m and 61 m O.D. Up to 1.5 m of this till was seen by these authors in the Lower Beane Valley and in the Hertford area at Braziers Pit (TL336127) lying within the Vale of St Albans. The apparent absence of this till elsewhere in the Vale and a preferred clast orientation of 115/295 ^{o} at Waterford (TL305150), led these authors to conclude that it was laid down by an ice lobe that advanced through the Hitchin Gap and down the Lower Beane Valley.

Clayton & Brown's middle till complex consisted of impersistent bands of chalky till interspersed with sometimes massive silts, clays and fine sands, interpreted as lacustrine deposits. The latter were found at approximately 69 m O.D. at Waterford. A large proglacial lake (Lake Hertford), was proposed, formed by damming of the Thames in the eastern part of the Vale of St Albans (Brown, 1959). It was suggested that this middle till was deposited by a lobe of ice advancing down the Beane Valley and extending into the lake. At Waterford, these authors obtained a macrofabric of 140/320^{o} which agreed with a previous fabric of 120/300^{o} recorded at Stapleford (TL308152) by West & Donner (1956).

The upper till, found mainly between 60 m and 70 m O.D., was described as a typical chalky till, with a fabric of 055/235^{o} at Waterford. This till was not well exposed in the Hertford area, but was assumed to represent part of a widespread sheet of surface till found across the region and to be equivalent to the Springfield Till that moved into Essex and East Hertfordshire from the east (Mitchell *et al.*,1973).

However, fabric data collected and analysed by Clayton & Brown (1958) and West & Donner (1956) was not subjected to significance tests and must be therefore treated with caution. These fabrics disagree with those obtained by Cheshire (1986) (see below).

Subsequently, Brown (1959) considered these deposits to have been laid down during repeated re-advances during the same glaciation and rejected the proposal of West & Donner (1956) that deposits of two distinct glaciations were represented.

3.12.3. Gibbard (1974, 1977, 1978a,1978b, 1983)

Gibbard described the Anglian sequence in the Vale of St Albans. This area stretched from Watford to Ware and therefore encompassed the Lower Beane Valley, taking in some of the sites of Clayton & Brown (1958). Investigation of pre-glacial gravels showed the current Beane Valley to mark the route of a northern tributary to the proto-Thames.

Two lodgement tills, both assigned to the Lowestoft Formation, were seen at Waterford (TL305147), Stapleford (TL316170) and Froghall Quarry (TL208204 - Cheshire's 'Frogmore' site) - the earlier Ware Till and the more extensive Eastend Green Till. From the stratotype at Westmill Quarry (TL342162), Gibbard was able to trace the Ware Till into the Hertford area and up the Beane Valley to Froghall. Basing his correlations on height, stratigraphic position and stone orientations only, he did not trace this till west of Hertford. He therefore concurred with the proposal of Sherlock & Pocock (1924) and Clayton & Brown (1958) that the ice had reached Waterford via the Hitchin Gap and Beane Valley and then turned southeast towards Ware. Here it met the proto-Thames and Gibbard claimed that, by continuing in a southeasterly direction, it dammed the river. A series of lacustrine silts and laminated clays were recorded northwest of Ware (Watton Road Silts). This lake, which was in existence for at least 500 years, was later overridden by the Ware Till ice. Gibbard obtained macrofabrics in the Lower Beane Valley and in the vicinity of Ware showing this ice to have a northwest-southeast trend. His data were supplemented with borehole logs throughout the Stevenage Valley providing a correlation with deposits as far as Fishers Green (TL224260) (Gibbard, 1977).

Following this advance, Gibbard (1977) claims that the Ware Till ice decayed *in situ.* He found evidence of this in slumped and flow tills in the Lower Beane Valley and in the vicinity of Ware, together with remnants of a braided channel deposited onto stagnant ice at Watton Road Quarry (TL343152). After an interval of unknown duration a proglacial outwash stream entered the Vale from the northeast, followed by deposition of the extensive Eastend Green Till.

An assessment of the extent and spread of the Eastend Green Till was obtained with difficulty. The typesite is at Waterhall Farm (TL297105). Based on height and stratigraphic position, it appeared to be represented by the upper till at Froghall Quarry (TL208204), Waterford (TL305147), Watton Road (TL343152) and Westmill Quarry (TL342162). Further correlatives of this till were also found as far west as Moor Mill (TL143025) in the Vale of St Albans.

3.12.4. Cheshire (1983a, 1983b, 1986)

The stratigraphy proposed by Gibbard was revised following further detailed work at 79 sites in Hertfordshire and west Essex and in particular on the extensive deposits at Westmill Quarry (Figure 3.6). Here, over 20 m of Pleistocene deposits gave Cheshire (1986) the opportunity to conduct an in-depth lithostratigraphic investigation. He found evidence of three separate glacial advances, the first of which, depositing the Ware Till, was seen to extend across to the western end of the Vale of St Albans. Equivalence was established through the analysis of particle size in the fraction down to +4.5 phi, the carbonate content and the small clast lithology in the fraction -1.5 phi to +1.5 phi. Statistical comparisons were made using multivariate analysis and similarity coefficients. Till samples were taken from 36 sites west of Westmill, resulting in the recognition of the westward extension of the Ware Till throughout the Vale of St Albans as far as Moor Mill and Bricket Wood (TL143024). This was in disagreement with Gibbard (1974, 1977) who claimed that the only till in this part of the Vale was his later Eastend Green Till. A middle till at Westmill - the Stortford Till - was found in the form of lenses or channel infill within the Ware Till. It extended mainly to the southeast and east of the study area. The continued presence of the, perhaps stagnating, Ware Till ice may have been responsible for the limited extent of the Stortford Till ice advance (Cheshire, 1986; Allen *et al.,*1991; Bridgland & Cheshire, 1994). Gibbard had correlated the upper till at Westmill Quarry with his Eastend Green Till at the typesite northwest of Hertford (TL297106). Cheshire, however, was unable to confirm this correlation, since his analyses showed that the till at Eastend Green, in common with all other lower tills in the Vale of St Albans, possessed a very strong statistical similarity to the Ware Till at Westmill. He therefore recognised the upper till at Westmill as the stratotype for the newly-designated Westmill Till, which extends only as far west as Hatfield. This till represented the final re-advance and is seen in the Lower Beane Valley. It was also shown at Westmill that gravels lying below the Ware Till (Westmill Lower Gravels) represented the final aggradation of the Thames prior to diversion by the ice, whereas those above this till (Westmill Upper Gravels), marked the first aggradation of the River Lea. Thus, the Thames had been diverted by the more extensive Ware Till ice and not as Gibbard claimed, his later Eastend Green Till ice.

Cheshire's Ugley Till, of more limited extent, was recognised only in the vicinity of Ugley Park Quarry (TL520280) and the Foxholes area of Hertford (Cheshire, 1986; Cheshire & Bridgland, 1994). He also believed the lower tills of Clayton & Brown (1958) and Gibbard (1974) in the Beane Valley were also part of the Ware Till, the uppermost till here being equated to his Westmill Till. Cheshire's fabric studies indicated that in general these ice advances, including that of the Ware Till ice, approached the Vale of St. Albans from the northeast in contrast to the previous authors who considered the likely path taken by the Ware Till ice was down the Lower Beane Valley. Macrofabrics obtained by Cheshire at Frogmore Quarry (059/239^{o} & 075/255^{o}) and Watton Railway Station (067/247^{o}) were all highly significant. Cheshire agreed with Gibbard however, that topography had influenced the path of the Ware Till ice, but that the early topographic influence was exerted by the North Hertfordshire Chalklands rather than by the relatively subdued relief of the lower proto-Beane Valley.

3.12.5. Summary

Two contrasting views are held relating to the direction of ice approaching the Vale of St Albans. Early work suggested that ice streamed through the Hitchin Gap and Lower Beane Valley to reach the Vale northwest of Hertford (Sherlock & Pocock, 1924; Sherlock, 1947; Clayton & Brown 1958; Gibbard, 1974). Gibbard (1974) believed that this ice was responsible for damming the proto-

Thames, whilst Sherlock & Pocock (1924) suggested it met up with ice that entered the Vale of St Albans from the northeast. Cheshire's evidence, however, suggests that the ice approached the sites within the Lower Beane Valley from a northeasterly direction, i.e. across the interfluves, rather than following the course of the Valley (Cheshire, 1986). Gibbard considered the Ware Till to have a rather restricted extent in the Hertford region, whereas Cheshire considered it to extend widely across the landscape at this time, correlatives being found on the North Hertfordshire Chalklands and in the Stevenage area.

The advance that followed the decay of the Ware Till ice deposited the extensive Eastend Green Till of Gibbard (1974, 1977) whereas Cheshire (1986) showed two minor re-advances – depositing the Stortford and the Ugley Tills - occurred before the more extensive final advance which deposited the Westmill Till.

3.13. North of the study area.

3.13.1. The Wash & Fen Basin

Most workers are in general agreement with the traditional model of ice advance into lowland Britain during MIS 12 proposed by Perrin *et al.* (1979) and outlined by Gibbard (in Clarke *et al.,* 2004). This proposes that ice moving south down the west side of the North Sea Basin entered the Wash and from there spread out in a fan-like fashion across East Anglia. This model has since been challenged by Rose (in Clarke *et al.,* 2004) who suggests that the above pattern of ice advance took place in MIS 10 and was preceded by an advance into western East Anglia from the northwest during MIS 12. A review of the Anglian palaoegeography and deposits lying immediately up-glacier of the current study area will therefore be of great value to the current work.

Controversy exists as to whether the Wash itself was excavated entirely by the Anglian ice or whether it represents a pre-Anglian fluvial basin subsequently glacially modified. Perrin *et al.* (1979) considered that the Wash and Fen Basin were created during the advance of the Anglian ice, the soft bedrock of the area being excavated by the ice as it advanced southwards. The result would be the creation of subglacially eroded basins subsequently infilled by till. The high quantities of Jurassic clay incorporated into the matrix of the till supported this contention. Rose (in Clarke *et al.,* 2004) proposed that this erosion occurred during both MIS 12 and MIS 10. However, Horton (1970) and Gallois (1994, 1999) believe the Wash to be the site of a major pre-glacial northerly flowing river (the Wash River). This is suggested by a series of deep drift-filled channels, thought to represent the remnants of a network that drained the Fen Basin and breached the Chalk escarpment before joining the Wash River and subsequently entering the North Sea. A southerly advancing ice sheet would have substantially modified this fluvial system, passing through the Wash gap and into the area of the Fens causing considerable erosion of Mesozoic sediments.

Rose (1987, 1994) and Bateman & Rose (1994) determined the course of the Bytham River, which they suggest ran from west to east across the Fenland area and the Cretaceous escarpment. It carried Triassic red, brown and purple quartzites and Carboniferous lithologies from the east Midlands. Remnants of these river deposits exist in the form of sands and gravels either side of the Fen Basin including the Bytham Sands and Gravels in Lincolnshire and the Ingham Sands and Gravels East Anglia (Lewis 1993). Gallois (1994) speculated that the system of drift filled channels may link up with those investigated by Horton (1970), who proved the existence of substantial depressions at several points along the valleys of the rivers Ouse and Ivel between Biggleswade and Huntingdon.

According to Rose (1994), the Bytham River brought lithologies including quartz and quartzites from the Midlands and cherts from the southern Pennines into the area of the Wash. Subsequently they were incorporated into the Anglian ice and carried south, together with local lithologies, to be deposited across a wide area of East Anglia and perhaps the southeast Midlands. The Bytham River itself would have been completely destroyed during this advance (Rose, 1994). However, Gallois (1999) disagreed with this proposal, disputing the existence of evidence for such a river in the Fenlands. A compromise suggested by Brew (1997) was that a west-east running Bytham river may have connected with the north-flowing Wash River.

The Fen Basin contains sediments of Anglian to Holocene age (Gallois, 1999). An extensive sheet of surface chalky Jurassic till continues under the Holocene sediments. Although generally less than 10 m thick on the interfluves and valley sides, depths of over 80 m are reached in drift filled valleys close to Kings Lynn. Also reported was a lower darker till overlain by a lighter more chalky layer (Gallois, 1999). Although earlier thought to represent a two stage ice advance, Gallois felt it more likely that the lower layer represented a basal layer of slower moving ice. He examined the erratic content of the till along the eastern edge of Fenland and also determined the likely direction of ice advance to be from the northwest, as shown in the earlier advance of Rose (1992) (Section 3.17.2).

Peterborough lies on the edge of the Fen Basin, approximately 52 km north of the study area, between East Anglia and the Midlands. Tills within the former region have been widely accepted as originating from the Anglian Glaciation (MIS 12), but Midlands tills have been the subject of some controversy. Both Horton (1981) and Davey (1991) considered tills from both of these regions to be “lithologically indistinguishable" and following Perrin *et al.* (1979) most workers have now accepted an Anglian age for these tills, although some (e.g. Rose in Clarke *et al*., 2004) claim them to originate from a later post-Hoxnian, pre-Ipswichian glaciation.

Straw (1984) considered the possibility that a ’Wolstonian’ advance was responsible for a major part of the excavation of the Fen Basin. The argument for this rested upon the lack of Hoxnian deposits within the basin, which would, it was felt, have been inundated during this interglacial following excavation by Anglian ice. It is possible that the Fen Basin was modified by a ‘Wolstonian’ glaciation. However, if the work of Perrin *et al.* (1973, 1979) in determining the Fens to be the source of the clays within the chalky till matrix is correct, the creation of the basin during a later glaciation seems unlikely, as in many places in eastern England the chalky till is overlain by proven Hoxnian deposits. Evidence of a post-Hoxnian pre-Ipswichian cold period in the Fen Basin is provided by a series of sands and gravels forming a delta-like feature at Tottenhill (Gibbard *et al.,* 1991). In a review of the stratigraphy of the Fen Basin, Bridgland *et al*. (1991) proposed three cold stages between the Anglian and Devensian, although not all necessarily representing full glacial conditions.

Langford (1999) suggested the drift-filled valleys of the Great Ouse relate to pre-Anglian drainage. He also suggested that the Edworth and Hatley Channels (Section 3.8.5) may have formed part of this drainage system, leading eventually to the Wash.

3.13.2. Witham on the Hill (TF055165).

This site in Lincolnshire lies some 50 km almost due north of the study area and has been investigated by Lewis (1993), Fish (2000) and Fish & Whiteman (2001). The Heath Till found here was considered part of the Lowestoft Formation by Perrin *et al.* (1979). However, this till is chalk-free, suggesting provenance to the northwest (Fish, 2000; Fish & Whiteman, 2001). On the basis of its lithology, Fish (2000) re-interpreted it as part of the Thrussington Till of the East Midlands, described in Section 3.17.1, which in turn is considered by Rose (in Clark *et al.,* 2004) to form an early part of the Lowestoft Till advance in MIS 12 (Section 3.17.3). Lewis (1993) reported macrofabrics showing a change in clast orientation from an early NNW-SSE direction to a later northeast-southwest direction.

3.14. West of study area

Horton *et al.* (1974) reported extensively on the area of Milton Keynes but Pleistocene deposits there have received little attention since then. Till occurs over more than half of this area, where it takes the form of a grey chalky , silty clay with angular flints, Bunter pebbles and Carboniferous sandstones, together with local limestones and fossils. Where weathered at the surface, selenite was also reported.

West of the study area reports of two stratigraphically superposed till units are numerous. These are described below.

3.14.1. Lower Till

Horton *et al.* (1974) reported a non-chalky lower till in an area to the north-west of Haversham in the Milton Keynes area. Found in a series of small outcrops on the lower valley sides, it is described as a gritty clay with fewer erratics than the chalky till, containing Bunter pebbles, local limestones and fossils, together with minor weathered flints. This is likened to the lower till of the Towcester district and Horton also suggested it to be similar to 'lower boulder clay' of Hollingworth & Taylor (1946) in the Kettering area, although the latter authors described this as flint-free. In the Milton Keynes region, Horton suggested this till could originate from an earlier glaciation or that it could represent earlier material re-deposited by ice at the front of chalky till ice sheet, where a great deal of local material would have collected. It does seem likely, however, that if the latter proposal is correct, the till would contain some chalk fragments.

The lower till of Kettering was believed to have been deposited by ice moving southeast across Lincolnshire, along a path west of the Chalk Wolds. It is separated from the upper till by the 'Mid Glacial Gravels' of Hollingworth & Taylor (1946). Shotton (1953) believed it to be much older than the chalky till.

3.14.2. Chalky Upper Till

The upper chalky till is mainly spread over the plateaux. A varying quantity of chalk gives rise to descriptions ranging from dark grey clay to pale bluish grey marly clay. A general tendency is noted for chalk and flint to increase towards the surface (Horton *et al.*,1974).

Much of the till in the Milton Keynes area was laid down within a lake sequence and a detailed account of a repeated transition from glaciolacustrine clays to till was recorded from Deanshanger by Horton (1970) and Horton *et al.* (1974). This sequence was recorded over a depth of 63 m and provides evidence of a proglacial lake which was over-run by the advancing chalky till ice on three occasions. These sediments are located in a depression within the Ouse Valley, being one of a series of such drift-filled depressions developed in the valleys of the Ouse and Ivel.

Closer to the study area, 3 km to the west of Leighton Buzzard, there appears to be a series of tills interleaved with lenses of sand and gravels. At the former brickworks pit at Littleworth, Wing (SP881232), Davies (1915) recorded up to 0.8 m of chalky till separated from a lower till by approximately 3 m of sand and fine gravel. Whilst there was no detailed description, the lower till was of very limited lateral extent, and its base was frequently difficult to differentiate from the local bedrock due to the amount of local clay incorporated. Close by, at Ascott Farm, a further sequence of two tills alternating with sand and gravel deposits was logged (Wyatt *et al.,* 1988). It is probable that this resulted from a minor retreat and re-advance of the margin of the ice sheet, similar to those seen further southeast in the Vale of St Albans.

3.15. East of study area

3.15.1. Barrington

Barrington lies just beyond the easternmost margin of the current study area. The brick pits here have been the subject of considerable research. One of the earliest reports is that of Hughes (1911) which, although concentrating on the vertebrate-rich Barrington Beds, makes mention of "a heavy mass of lead coloured boulder clay" capping a hilltop to the north. Since then a series of studies have been conducted on the tills at this site, with somewhat contradictory results.

Baden-Powell (1948) and West & Donner (1956) in their regional studies, concluded that both Lowestoft and Gipping ice passed over the Cambridge Area. But the latter authors reported evidence of only the Lowestoft Till at Barrington and on the adjoining Western Plateau of Sparks (1957), with an east-west oriented macrofabric. Additional studies by Sparks (1952) and Forbes (1959) also failed to find definite evidence of multiple tills.

Norris (1962) claimed to detect evidence of two separate advances. Following an investigation of lithologies, fabrics and erratics, he felt able to identify both Lowestoft and Gipping Tills at Barrington. This was achieved on the basis of :

a) colour, the older till being darker.

b) differences in height.

c) lithological differences – in particular pink chalk being ubiquitous in the upper till but absent in the lower.

d) stone orientations.

The colour of a till can be variable, depending on degree of weathering and composition and is therefore an unreliable criterion on which to differentiate tills, as is the difference in height. The presence of pink chalk (presumably clasts of Red Chalk) in the upper till is also noted in south Hertfordshire (Little & Atkinson, 1988) and throughout the present study area.

However, Norris was unable to obtain a suitable fabric from the Lowestoft Till, possibly because of the lack of rejection criteria employed when selecting suitable clasts. Measurements included those of clasts in close proximity to each other, or in contact, presenting similar orientations which would have been responsible for erroneous results. He observed significant local variation of fabrics over a vertical height of approximately 0.6 m. He did however, feel there were "obvious differences" in the stone orientation between the upper and lower tills. Norris recorded up to 2 m of Lowestoft Till resting on Chalk, directly overlain on the interfluves by up to 4.5 m of oxidised Gipping Till. In places the two were separated by chalky solifluction deposits. Norris commented that "due to their superficially similar lithologies the upper and lower tills were only differentiated with difficulty" (Norris, 1962). It was made clear in this paper that he had relied heavily on the patterns of ice advance suggested by West & Donner (1956) in his interpretation of the stratigraphy at this site.

A small study by Fuller (1962) reached the same conclusions as Norris when he removed oriented blocks of till from the northwest corner of the chalk pit in order to test a new method of analysis involving the measurement of magnetic till fabric.

Worssam & Taylor (1969) accepted the presence of both Gipping and Lowestoft Tills within the Cambridge area, although they noted that their extent was too limited to attempt to reconstruct the glacial history.

Cox & Nickless (1972), Bristow & Cox (1973), Perrin *et al.* (1973) and the landmark paper by Perrin *et al.* (1979) suggested the presence of just one chalky till in East Anglia. Following these studies, Hoare & Connell (1981) re-assessed the deposits at Barrington. They conducted mineralogical and carbonate analyses along with mesofabric and macrofabric measurements.

Their conclusion was that only one till exists at this site, the lower sections being subjected to mineralization and discoloration due to raised groundwater levels during the Hoxnian, Ipswichian or early Flandrian. Contrary to the findings of Norris (1962), Hoare & Connell found Red Chalk present at all levels. They obtained fabrics indicating southerly moving ice assigned to the Lowestoft advance in line with Perrin *et al.* (1979). Various suggestions were made in this paper for the apparent disagreement with fabrics obtained by West & Donner (1956).

As part of a major study on till provenance, Fish (2000) also investigated the deposits at Barrington. Here once again, a distinction was drawn between an upper lighter layer of till and a lower darker layer. Using chalk-derived microfossils it was established that the two layers of till across the region in general had different provenance. This is discussed further in Section 3.17.3. However, at Barrington, although the two layers of till could be separated on the basis of chalk and limestone content, the microfossil content of both layers suggested an east to NNE provenance. Although interpreting till at Barrington as a deformation till, Fish reported a lack of deformation structures in the underlying Chalk. Hoare & Connell (1981) on the other hand, noted shearing and slickensiding in the underlying bedrock.

Lewis (1999) and Boreham (2002) refer to just one chalky till at Barrington – the Barrington Works Diamict.

3.15.2. Mid-Essex

The work of Clayton (1957) identified the Hanningfield, Maldon, and Springfield Tills, but did not provide sufficient detail to allow comparisons with the present study. Whiteman (1987) separated the tills of Mid-Essex into two members based on fabric characteristics and lithology (Whiteman, 1987). The lower, Newney Green Member, is a complex, sandy, reddish brown, commonly banded till up to 2 m thick. The base of this unit was subjected to glacial shear stress resulting in deformation and incorporation of the underlying Kesgrave Sands and Gravels. This till is, therefore, characterised by a high proportion of local clasts. Strong clast preferred orientation is seen trending between WNW-ESE and northwest –southeast. These macrofabrics were attributed to a compressive stress regime developed in response to the rapid incorporation of subglacial material as the ice passed onto the permeable Kesgrave Sands and Gravels.

Immediately above the Newney Green Member lies the Great Waltham Member. This is a massive, grey lodgement till typically containing far-travelled lithologies from northwest of the Chalk escarpment (Whiteman, 1991). Macrofabrics taken from this member, are normal to those in the Newney Green Member, and are considered to have been deposited under extensional flow conditions, representing the direction of ice advancing across Mid-Essex from the north. Associated with the Great Waltham Member are tills considered to have undergone some melt-out or secondary re-sedimentation during deposition.

3.15.3. Suffolk

Much of the discussion relevant to Suffolk is covered in Section 3.17.1, but of particular relevance because of its detail, is the work of Allen (1983) who identified four till lithofacies in the Gipping Valley.

The Creeting Hill Member is a brown/brownish yellow flow till present in lenses associated with outwash deposits and having a very limited distribution. The Broomwalk Member (formerly the Barham Till of Allen, 1983) is similar to the basal Newney Green Till in Essex (Section 3.15.2) in that deformation processes (shearing) have resulted in the incorporation of underlying sand and gravels. The Bramford Member is of variable colour and composition and is found on the valley sides. This till is deficient in silt and clay and is interpreted as a melt out till deposited by stagnant ice in the Gipping Valley. The most widespread till in this part of Suffolk is the Blakenham Member which is a dark grey clay-rich lodgement till. Macrofabrics from this till indicate ice movement in a northeast to southwest direction. A local variation in trends around the Stowmarket area is thought to be due to a rise in the sub-till surface, resulting in compressive ice flow and transverse macrofabrics.

At High Lodge (TL740754) in northwest Suffolk, Lewis (1992) described the Mildenhall Lower Diamicton. This yellowish brown till, up to 5.6 m thick, has a high proportion of local clasts together with minor quantities of Rhaxella chert, quartz, quartzite, sandstone, limestone and ironstone. Many lenses of silty sand and sand are also present within this till. Macrofabric analyses indicate considerable local variation in stress patterns, but consistent resultant vectors indicate ice flow from a direction slightly south of west.

3.16. Summary

The survey of neighbouring regions suggests that only in east Hertfordshire, Mid-Essex and Suffolk, has a detailed till stratigraphy been described. In eastern Cambridgeshire and west of Leighton Buzzard (Milton Keynes area) although a rough stratigraphy exists, detailed description of many of the deposits is lacking and no attempt at a regional correlation has been made.

The tills studied in east Hertfordshire, Mid-Essex and Suffolk lie at the southern margin of the Anglian till sheet which is mainly a homogeneous grey lodgement till, although slumped, melt-out, and deformation tills are also found. In general across Mid-Essex and Suffolk a lower deformation till is present, where incorporation of underlying Kesgrave Sand and Gravels is found. In Hertfordshire, tills record an oscillating ice margin, perhaps due to periodic fluctuations in ice volume causing over-topping of the Chalk scarp barrier (Allen *et al.,*1991). In all three of the areas mentioned above, the tills are interpreted as deposits of a single glacial episode.

A chalk-free till is found to the north of the study area at Witham on the Hill (Fish, 2000) and to the west in the Milton Keynes area (Horton, 1970) where it lies beneath a chalky till.

Table 3.5 presents a summary of stratigraphies described in this chapter. It should be noted that lateral position in the diagram does not necessarily imply stratigraphical equivalence.

3.17. Patterns of ice flow.

Although considerable research has been conducted in both East Anglia and the Midlands, very little work has been focused on petrographic analysis for stratigraphic correlation. The area currently under study lies between these areas and the sites under investigation here have at times been included in research concerned with either or both of these areas.

<table>
<tr><th>Milton Keynes area Horton *et al.* (1974)</th><th>Leighton Buzzard area Shephard-Thorn *et al.* (1994)</th><th>Hitchin Channel Hopson *et al.* (1996)</th><th>Stevenage Channel Hopson *et al.* (1996)</th><th>Vale of St Albans Gibbard (1974,1977).</th><th>S. Herts & W Essex Cheshire (1986)</th><th>Cambs. Worssam & Taylor, (1969) Boreham (2002)</th><th>Mid-Essex Whiteman (1987)</th><th>Suffolk (Allen, 1983)</th></tr>
<tr><td rowspan="8">Sands and gravels of unknown age
Till with glacial sands & gravels
Glacial lake deposits</td><td rowspan="9">Till
Glacial sand & gravel
Glacial lake deposits
Buried channels of Ouzel & Lea</td><td colspan="2">Hitchin Formation</td><td>Hatfield Member</td><td></td><td rowspan="9">Observatory Member
Barrington Till (Barrington Works Member)
?Glacial Loam
Glacial sands and gravels</td><td rowspan="2"></td><td rowspan="9">Haughley Park Member (outwash)
Blakenham Member
Bramford Member
Broomwalk Member
[Creeting Hill Member]
Shrubland Member (proximal outwash)
Sandy Lane Member (distal outwash)</td></tr>
<tr><td colspan="2">Glaciofluvial outwash & postglacial fluvial deposits</td><td></td><td></td></tr>
<tr><td>Vicarsgrove Till</td><td>Graveley Till (Graveley Member)</td><td></td><td rowspan="5">Westmill Till (Wadesmill Member)
- - - - - - - - - - - -
[Ugley Till (Ugley Member)]
Westmill Upper Gravel (Hertford Member)
[Stortford Till (Stortford Member)]</td><td rowspan="7">Great Waltham Member
Newney Green Member</td></tr>
<tr><td colspan="2">Maydencroft Till (Maydencroft Member)</td><td>Eastend Green Till (Eastend Green Member)</td></tr>
<tr><td colspan="2">Glaciofluvial outwash</td><td rowspan="3">Westmill Upper Gravel (Hertford Member)</td></tr>
<tr><td colspan="2">Charlton Till (Charlton Member)</td></tr>
<tr><td>Glaciolacustrine deposits
(Thistley Farm Member) subglacial fluvial deposits</td><td>Glaciolacustrine deposits
(Thistley Farm Member)</td></tr>
<tr><td>Priory Till (Priory Member)</td><td>Stevenage Till (Stevenage Member)</td><td colspan="2">Ware Till (Ware Member)</td></tr>
<tr><td>Fluvioglacial deposits</td><td>Glaciofluvial outwash and subglacial fluvial deposits</td><td>Glaciofluvial outwash</td><td colspan="2">Westmill Lower Gravel (Westmill Member)</td></tr>
</table>

Table 3.5. Summary of regional stratigraphy.

Note: Lateral position in the diagram does not necessarily imply stratigraphical equivalence.

3.17.1. Early Research

Both areas possess large tracts of chalky till, but historic differences in interpretation and methodological approach has led to different conclusions regarding age and stratigraphy. Thus the number and direction of advances is still debatable.

For more than 100 years researchers have considered the character and origin of the ice responsible for deposition of the widespread chalky till. That the ice moved from a general northerly direction is clear, with the exception of the extreme north and northeast of Norfolk, where controversy now exists regarding the presence or otherwise of contemporaneous Scandinavian ice (Moorlock *et al.,* 2001; Lee *et al*., 2002; Rose in Clark *et al*., 2004; Hoare *et al*., 2006). It is generally believed that the tills covering Midland and eastern England indicate ice moving down from northern England and the Scottish highlands.

Suggestions concerning the exact path of the ice into these regions are outlined below.

East Anglia

East Anglia possesses the most complete record of Quaternary sediments in the U.K. It was considered at the end of the 19th century that the tills of this region could be separated on the basis of colour and lithological composition (Baden-Powell, 1948).

Work based on the erratic content of tills by Harmer (1907) indicated an approach of ice from the west and northwest, entering Fenland from Lincolnshire, before moving out in a fan like pattern across central and eastern England. To explain an anomalous distribution of lithologies west of the Fens, Harmer invoked cross currents within the ice sheet. Baden-Powell (1948) disliked this idea and suggested two episodes of chalky till deposition. He claimed that the two tills could be differentiated by matrix composition, erratic content and colour and that the presence of two ice sheets better explained Harmer's findings. The lower till became known as the 'Lowestoft boulder clay' and the upper he named the 'Gipping boulder clay' following detailed descriptions in the Gipping Valley. Ice flow models, based on matrix and erratic

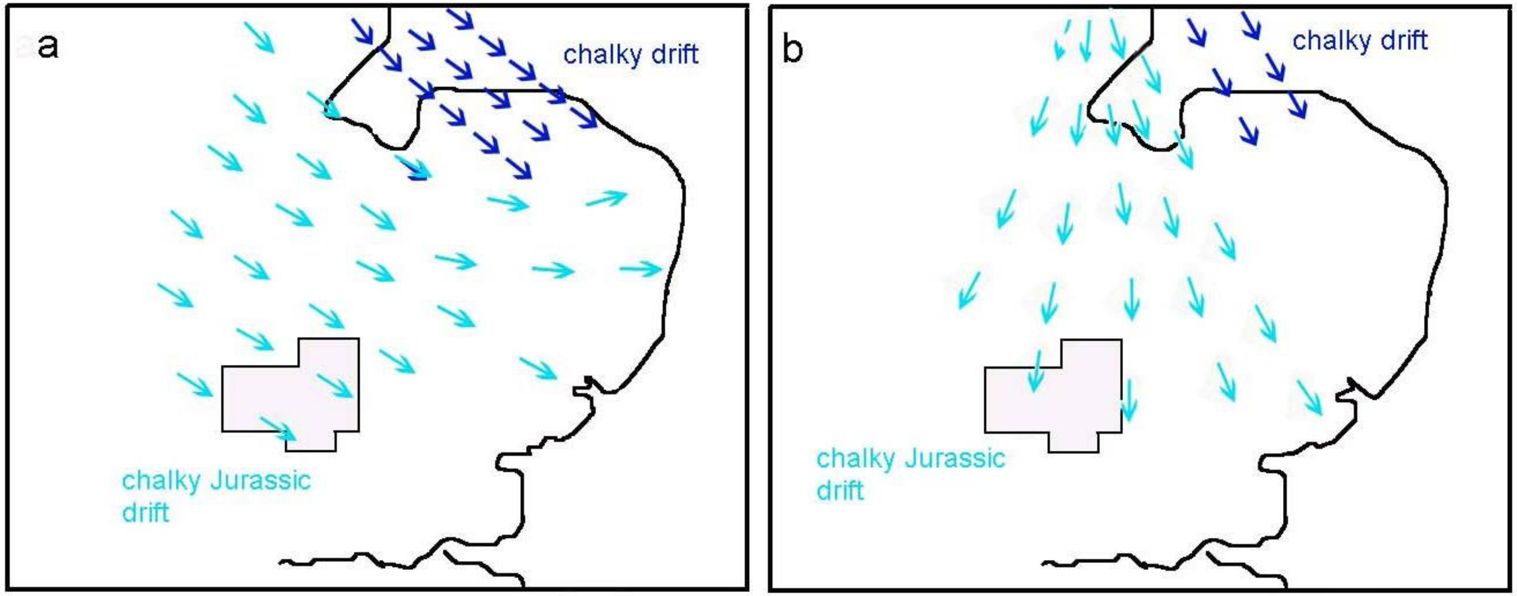


Figure 3.7. Patterns of ice advance suggested by Baden-Powell (1948) for
a) Lowestoft advance and b) Gipping advance. Study area shown for reference.

(modified from Baden-Powell,1948)

content for both glaciations are shown in Figure 3.7. There was no universal agreement on the limit of the Gipping Glaciation, although Woodland (1970) considered it to have covered the whole of Suffolk, together with a good deal of Essex and Hertfordshire. Baden-Powell (1948) considered the two tills to be separated by Hoxnian interglacial deposits. These two glaciations were thought equivalent to the Elsterian and the later Saale Glaciations of Europe (Mitchell *et al.,* 1973) now recognised as equivalent to MIS 12 and MIS 10 respectively.

The work of West & Donner (1956) shown in Figure 3.8, based purely on fabric data, supported both the presence of two separate tills and Harmer's direction of advance. Their findings indicated early Lowestoft Till ice approached from the south Pennines, moving in a southeast to east-southeast direction across the current study area and fanning out to the north and south across East Anglia. The later Gipping advance moved out from a centre north of the Wash, radiating out across East Anglia and as far west as Moreton-in-Marsh.

Thus, these studies agree on an initial advance from the northwest and a subsequent (Gipping) advance from a north or north-northeasterly direction across the study area.

Ice advances across the Midlands

Establishment of the Pleistocene sequence of the Midlands was achieved by reference to the biogenic deposits in the Severn Valley (Shotton, 1953). Wills (1924) recognised two glaciations which were correlated with the Elsterian and Saalian, the latter being considered responsible for deposition of the 'main eastern' glacier east of the Pennines.

Baden-Powell (1948) believed his model of glaciation in East Anglia agreed well with the sequence found in the Midlands. The Pennine ice advancing from the northwest resulted in deposition of the lower Lowestoft Till, the upper till being part of the East Midlands chalky till sheet. The glacial deposits were distinguished on geomorphological evidence – deposits lying more than approximately 60 m above the valley floors, deeply dissected and very poorly preserved, were considered to be Elsterian (Clayton, 1979). These included the 'Lower Boulder Clay' of Hollingworth & Taylor (1946) in Northamptonshire.

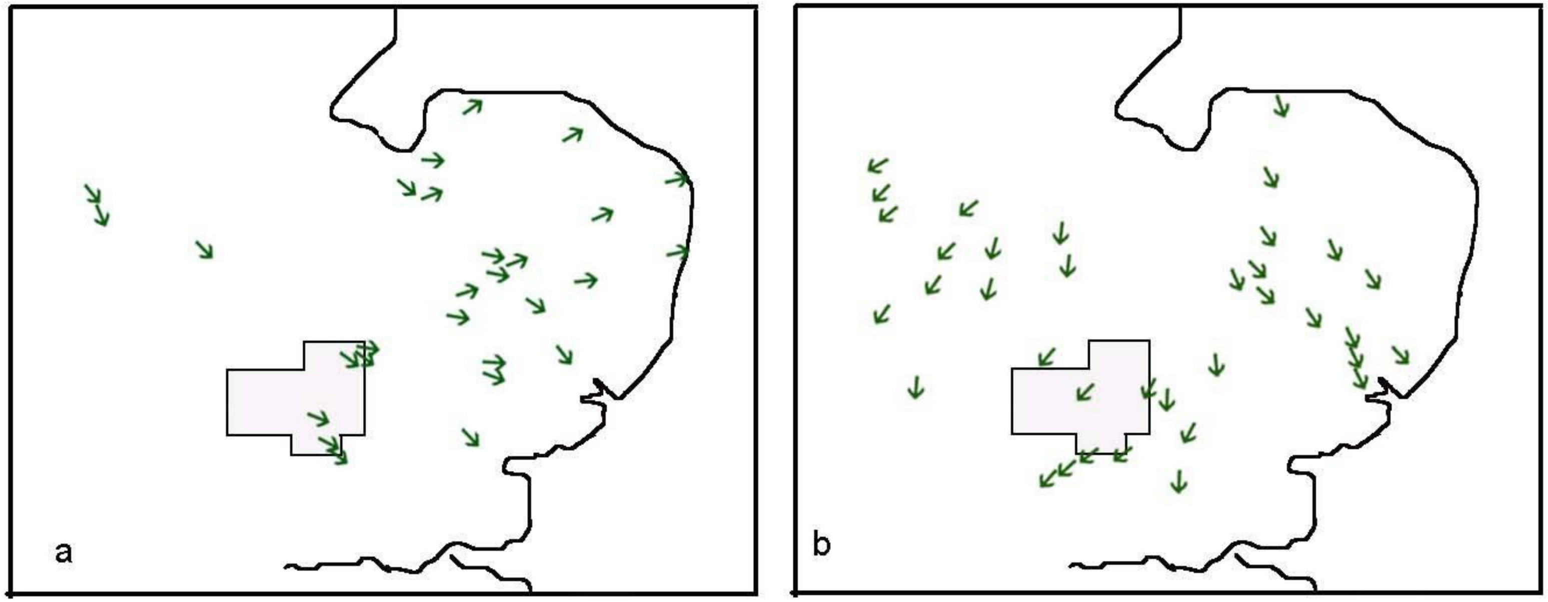


Figure 3.8. Pattern of ice advance suggested by West & Donner (1956) for a) Lowestoft advance b) Gipping advance. Study area shown for reference. (modified from West & Donner, 1956).

In 1953 Shotton described a series of glacial “Wolstonian” deposits at Nechells (Birmingham), which appeared to overlie organic deposits assigned to the Hoxnian. This was therefore proposed as evidence of a major post Hoxnian pre-Ipswichian 'Wolstonian' glaciation. Deposits here recorded two advances during this glaciation. Ice approaching from the north deposited a lower (Thrussington) till being Trias-rich with little or no chalk and flint and separated from tills of the later ice by extensive lacustrine deposits. The second advance coming from the northeast brought Cretaceous material and was responsible for the chalky Oadby Till. This sequence of deposits was confirmed across an area extending from Leicester to Coventry and south to Moreton-in-Marsh (Bishop, 1958; Rice, 1968, 1981). Clayton (1979) considered that the second advance from the east may have been a result of ice gaining strength as it streamed through the Wash, the latter having been scoured and deepened during the earlier Anglian Glaciation. Consequently it was able to spread as far west as the Cotswolds.

At the southern limit of the Wolstonian advance, Clayton (1979) inferred the presence of an ice lobe extending towards the Thames, lying between the unglaciated Chiltern and Cotswolds cuestas. The eastern limit was much harder to define, but it was suggested that the tills of East Anglia were of Anglian age and Midland tills were of Wolstonian age. However, as pointed out by Perrin *et al.* (1973, 1979 - see below) these tills form one continuous sheet of very similar composition.

3.17.2. Re-interpretation by Perrin, Rose & Davies (1979).

Following the mapping of the Chelmsford and Norwich areas, Bristow & Cox (1973) re-examined evidence for the existence of the Gipping Till. In the same year Perrin *et al.* (1973) published results of lithological studies of the chalky tills. Neither could find any evidence to support the existence of a separate Gipping Till. In fact the remarkable constancy of composition of the matrix of all tills across the area was noted by Perrin *et al*. (1973).

Results of a major study involving extensive quantitative lithological study of pre-Devensian tills were later published by Perrin *et al*. (1979). 501 samples from 289 sites were examined and the results revealed a division into two groups: the North Sea Drift type and the Lowestoft type tills. The latter group included not only the Lowestoft Till of East Anglia, but also the chalky tills of the East Midlands and the Calcethorpe and Wragby tills of Lincolnshire. Mineralogical data pointed to an origin for both groups in the North Sea. They concluded that all these tills were deposited during a single glaciation. The proposed pattern of ice advance differed from that of Baden-Powell's Gipping advance, in that an ice stream passed down the east coast and the western margin of the North Sea to pass through the Wash Gap, excavating the Mesozoic clays and then radiated out over the East Midlands, Lincolnshire and East Anglia. This concept was supported by work undertaken by Clayton (2000) who calculated the volume of excavated material from the Wash and Fens to be roughly equivalent to the volume of chalky till present in east Anglia. This model implies an ice sheet approaching the study area from the north or northeast (Figure 3.9a). They concluded that all the tills in their study were likely to be of Anglian age (MIS 12), although this was not a view shared by all (Straw, 1979, 1984; Shotton, 1983, 1985, 1986).

A revision of this model was proposed by Rose (1992; 1994) (Figure 3.9b) who introduced an earlier phase of glaciation flowing southeast from the Pennines and moving across the study area in a direction reminiscent of that of the first advance suggested by West & Donner (1956) (Figure 3.8a). This revision was the result of work on fabrics and lithologies during investigations at High Lodge (TL739754) (Rose, 1992).

3.17.3. Subsequent Revisions

Fish (2000) considered the microfossil content of the chalk contained in both matrix and clasts. By locating the chalk strata from which the microfossils originated, he was able to suggest ice flow trajectories. However, although this research covered the whole of East Anglia and as far north as Lincolnshire and west to Leicestershire and Northamptonshire, conclusions were based on data from 15 sites, tills from only 12 of these being subjected to complete textural and lithological analyses. Nevertheless, like Baden-Powell (1948) and West & Donner (1956), he recognised two layers of till, an upper paler, chalkier variety and a lower darker type. He attributed these to a single glaciation, the lower till being laid down by ice that flowed south along the east

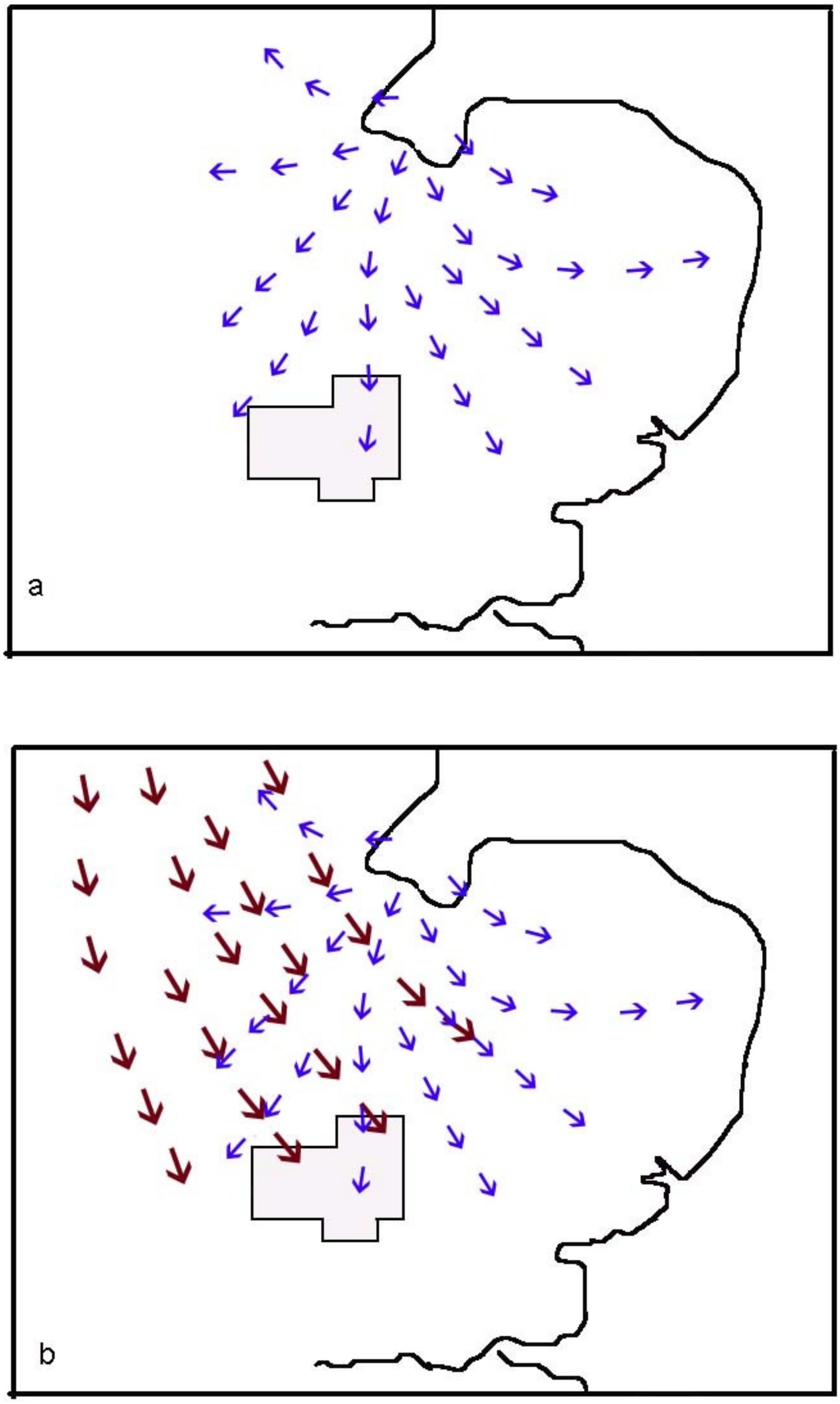


Figure 3.9. Suggested direction of ice movement

a) after Perrin *et al*. (1979)
b) two stage model of Rose, (1992) showing early advance from the northwest (brown) and later advance through the Wash (blue).

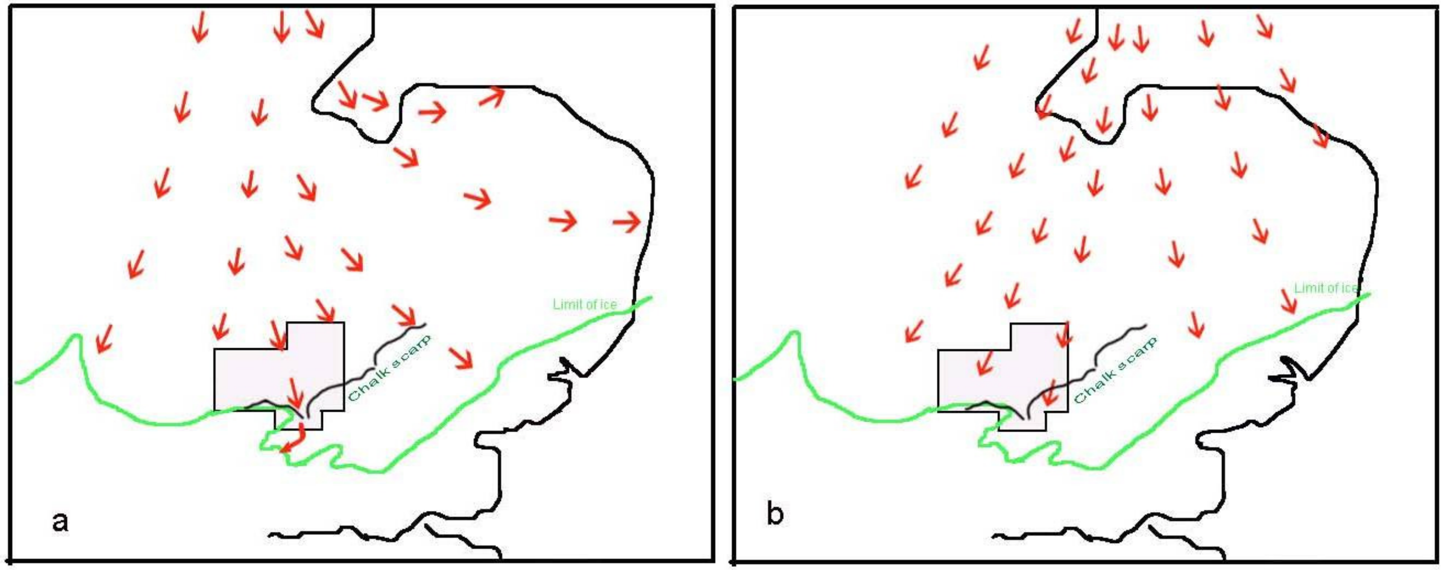


Figure 3.10. Patterns of ice advance suggested by Fish & Whiteman (2001).

a) Early part of Lowestoft Glaciation

b) Ice flow trajectory moves to the east during later part of Lowestoft Glaciation.

coast before fanning out over East Anglia (Figure 3.10). The upper till ice followed a similar pattern, with the locus of ice flow shifted eastwards, passing over a greater outcrop of chalk and resulting in the chalkier till (Fish & Whiteman, 2001).

A gradual transition was found between the lower and upper till. Fish (2000) believed that the shift in flow trajectory was related to the changing position of Scandinavian ice in the North Sea basin.

Major revisions were proposed to the stratigraphic succession in East Anglia by Hamblin *et al.* (2000). These revisions imply a more complex interpretation of middle and late Pleistocene events, suggesting a total of five glaciations and a re-assignment of tills of the Midlands to a Stage 10 glaciation.

Rose (in Clark *et al.,* 2004) gave details of his proposed new till stratigraphy. Deposits of an Anglian MIS 12 advance include the Jurassic and chalky facies of the Lowestoft Tills in East Anglia together with the Lower Till of Northamptonshire and the Thrussington Till of the east Midlands and probably the tills of Lincolnshire. This ice sheet is thought to have moved across the study area in a southeasterly direction before fanning out across East Anglia, much in the same fashion as described by West & Donner (1956). Rose, however disputed evidence for the presence of a Scandinavian ice sheet at this time.

Deposits of MIS 10 (which has not as yet been named), include the Jurassic and chalky Lowestoft Tills of the Midlands including the Oadby Till, together with part of the Lowestoft till and the Bacton Green Till in northeast East Anglia. Evidence that these tills may relate to a later glaciation comes from deposits found at Tottenhill within the Fen Basin, where peat overlying a till has been dated to MIS 9 (Bowen, 1991), thereby implying an MIS 10 date for the till (Gibbard *et al.,* 1991). Also Sumbler (1995) has shown that in the Upper Thames Valley the Oadby Till can be correlated with terraces dated to MIS 10. This advance is considered to be equivalent to the Saalian in northern Europe where very extensive glacial events are interrupted by short interstadials. Gibbard *et al.* (1991) commented that similar conditions should have occurred in

Britain at this time. MIS 10 ice is considered to originate in northern Britain travelling down the west side of the North Sea to spread as far as Derby in the west and Moreton-in-Marsh in the south. Upon reaching the Wash it moved out in a radial pattern, across East Anglia in a similar fashion to that suggested by Perrin *et al*. (1979). The eastern limit is undefined although Rose (in Clark *et al.* 2004) mentions a possible margin along the Chalk escarpment stretching from Luton to the Wash. However, Rose (2007) reported the results of field research and mapping carried out since the publication of Perrin *et al*. (1979). He defined an area where the chalky Jurassic till derived from the northeast overlies the Pennine and Jurassic till from the northwest (see Figure 9.1 in Chapter 9), although he considered that these deposits cannot be differentiated on lithological grounds from the underlying MIS 12 tills.

Discussion of the matter continues; some authors have proposed that the major ice advance now known as the Anglian may have extended across both MIS 12 and MIS 10 (Keen, 1999; Sumbler, 2001).