# CHAPTER 6
# MACROFABRIC ANALYSIS

## 6.1. Introduction

This chapter discusses the macrofabric measurements taken across the study area. The results, including information provided by eigenvectors and derived statistics, are discussed in relation to both the direction of advancing ice sheets and the mode of till deposition.

## 6.2. Creation of till macrofabric

Significant critical work on the creation of till macrofabrics was carried out in the 1970s and continues today.

Clasts can be subjected to significant stress regimes where ice shearing occurs, resulting in strong clast fabrics (Boulton, 1971). These can be the result of processes acting a) englacially whilst being transported within a body of ice and b) at the ice-sediment interface during deposition. Fabrics formed by a) can be preserved intact in till deposited by stagnant ice during an ice-front retreat phase. However, at the ice-sediment interface most englacial fabrics are to some extent modified during deposition by active ice (Lindsay, 1970; Dreimanis, 1990). This modification can involve re-orientation of clasts by dragging/rolling of the particle at the interface and deformation of sediment below the interface (Lindsay, 1970). Work carried out in modern glacial environments (Boulton, 1971; Lawson, 1979) has confirmed the preferred alignment of elongate clasts to be in the direction of principal stress, i.e. parallel to the direction of ice flow as suggested by Holmes (1941). This is due to the drag effects of the glacier sole, the substrate and/or the matrix flowing around clasts (Lindsay, 1970; Benn, 1995). However, compressive ice flow conditions may result in some clasts becoming oriented in a direction transverse to ice flow (Penny & Catt,1967; Boulton, 1971; Dreimanis, 1990; Carr & Rose, 2003).

As a result of these processes, subglacial/basal tills can possess a well-developed fabric with the principal mode reflecting the direction of former ice sheet movement, possibly with a secondary mode representing a transverse component. Most authors now agree that bimodal fabrics, exhibiting both parallel and transverse components, are common (Lindsay, 1970; Mark, 1974) and a compressive flow regime can result in a dominant transverse mode (Boulton, 1971).

Clast macrofabrics can also be produced or altered by post-depositional processes, particularly on slopes, by compaction, flow, shearing, folding and slumping (Lindsay, 1970). The subglacial environment is an extremely complex one and fabrics may be the result of overprinting of many repeated processes of deformation, erosion and deposition (Hicock *et al.*, 1996).

Macrofabric analysis, although providing information on the direction and dynamism of ice movement, is not considered an appropriate basis on which to differentiate till units. Local topography, in this case the presence of the Chalk escarpment and Hitchin channel, can dominate the fabric, making correlation difficult. Differentiation of till units is therefore addressed using other statistical methods in Chapter 7.

## 6.3. Descriptions of macrofabric properties

In most earlier studies, macrofabrics in the Lowestoft Till are described in terms of resultant vectors, vector magnitudes and dip values, such as are given in Chapter 5. However, more recently use has been made of eigenanalysis. Mark (1973) was one of the first to propose this method as an improvement on two dimensional fabric analysis. It involves representation of the data on three orthogonal eigenvectors. The first principal eigenvector ($V_1$) represents the axis of maximum clustering, the amount of clustering being represented by the normalised vector magnitude (eigenvalue) $S_1$ (Figure 6.1). $S_2$ and $S_3$ are the representative eigenvalues for the second ($V_2$) and third eigenvectors ($V_3$), the last representing the axis of minimum clustering (Andrews, 1971; Mark, 1974). The eigenvalues are used to calculate the isotropy (I) and elongation (E) indices, i.e. $I = S_3/S_1$ and $E = 1-(S_2/S_1)$. The isotropy index compares the fabric to that of a uniform distribution varying between 0 (all clast orientations confined to a single plane or axis) and 1 (perfect isotropy). The elongation index measures the preferred orientation in the $V_1/V_2$ plane, varying between 0 (no preferred orientation) and 1 (all clast orientations parallel). These indices are plotted on a triaxial (Benn) diagram (Benn, 1994) such as is seen later in Figure 6.2 in Section 6.5. Where shear stresses are high and a large proportion of clast a-axes are aligned in the same direction, a strong fabric exists and $S_1 >> S_2 \approx S_3$, plotting in the bottom right corner of the Benn diagram. Much lower stresses result in an isotropic distribution, i.e. a weak fabric with no preferred orientation, where $S_1 \approx S_2 \approx S_3$, plotting at the top of the diagram. This can be the result of an initially strong englacial fabric being modified at the ice-substrate interface. A planar girdle distribution with points evenly distributed around a great circle would yield $S_1 \approx S_2 >> S_3$ (Benn, 1994; Jones *et al.,* 1999) and therefore plots in the bottom left hand corner of the Benn diagram. According to Hicock *et al.* (1996) girdle fabrics are often associated with deformation tills.

## 6.4. Methods and objectives

Several borehole cores described in Chapter 5 were subjected to macrofabric analysis. At other sites with exposures, measurements were obtained from sediments immediately adjacent to material sampled for analysis. Sample details are given in Table 6.1. The data were subjected to statistical analysis described in Section 4.6.1, and resultant vectors, vector magnitude, average dip, statistical significance and results from the eigenanalysis are presented in Table 6.2.

In Section 6.5.2 the data are presented in the form of a bivariate plot of $S_3$ / $S_1$ eigenvalues (Figure 6.1) to provide a visual representation of fabric strength. In addition, the data are shown on a ternary diagram (Figure 6.2) scaled by fabric isotropy ($I = S_3/S_1$) and fabric elongation ($E = 1-(S_2/S_1)$) as described by Benn (1994). Process fields corresponding to work by Dowdeswell & Sharp (1986) on modern glacigenic sediments are overlain onto data from this study in Figure 6.3. Comparisons are also made with other studies of the Lowestoft Till as detailed in Section 6.5.3 and shown in Figures 6.4 and 6.5.

The specific objectives of this part of the investigation are as follows:

**1**. To assess any preferred orientation of clasts and thus evaluate the evidence for general direction of ice movement across the study area.

**2.** To determine whether evidence exists for ice movement being influenced by topography.

**3**.  To investigate the macrofabric evidence for a separate ice advance entering the study area from a northwesterly direction as suggested by Baden-Powell (1948), West & Donner (1956) and Rose (in Clark *et al.,* 2004).

4.   To compare results with regional fabrics reported by previous workers.

**5.**  Using eignenanalysis, to investigate fabric shapes of tills sampled during this study and compare them with published data.  The usefulness of this method for determining the process of till formation and strain history will be assessed.

| Site No. | Sample No. | Location | Grid Ref | Height (m O.D.) |
|---|---|---|---|---|
| 1 | 1 | Knebworth Park | TL2289 2150 | 102.3 |
| 1 | 2 | | | 104.2 |
| 2(U) | 4 | Norton Green | TL2288 2276 | 98.8 |
| 3(U) | 8 | Cannocks Wood | TL2240 2252 | 70.4 |
| 3(U) | 9 | | | 73.4 |
| 3(U) | 10 | | | 76.6 |
| 3(U) | 11 | | | 79.7 |
| 3(U) | 12 | | | 81.5 |
| 3(U) | 13 | | | 83.6 |
| 3(U) | 14 | | | 85.6 |
| 3(U) | 15 | | | 87.7 |
| 4 | 17 | Letchmore | TL2167 2430 | 116.0 |
| 5 | 19 | St Ibbs | TL1962 2662 | 68.8 |
| 6 | 20 | Little Wymondley | TL2107 2753 | 66.5 |
| 6 | 21 | | | 68.5 |
| 6 | 22 | | | 70.5 |
| 7 | 23 | Great Wymondley | TL2176 2846 | 81.5 |
| 7 | 25 | | | 85.5 |
| 8(M) | 27 | St Ippollitts | TL1960 2720 | 39.0 |
| 10 | 29 | Baldock | TL2346 3657 | 66.8 |
| 10 | 30 | | | 68.1 |
| 10 | 31 | | | 69.4 |
| 10 | 32 | | | 70.7 |
| 11(M) | 34 | Primrose Hill Quarry, Holwell | TL1676 3200 | 38.4 |
| 11(M) | 35 | | | 41.0 |
| 11(M) | 36 | | | 44.0 |
| 16 | 41 | Moggerhanger | TL1320 4805 | 53.4 |
| 22 | 49 | Cockayne Hatley | TL2555 4969 | 73.5 |
| 27 | 58 | Milton Bryan | SP9770 3045 | 132.9 |
| 30 | 63 | Heath & Reach | SP9314 2916 | 130.2 |
| 30 | 64 | | | 132.2 |
| 30 | 65 | | | 134.2 |
| 30 | 66 | | | 136.2 |
| 30 | 67 | | | 138.2 |
| 30 | 68 | | | 140.2 |

U= Upper till, M= Middle till

**Table 6.1. Samples subjected to macrofabric analysis.**

| Site No. | Sample No. | Resultant Vector (degrees) | Vector Magnitude (%) | Rayleigh Significance (%) | Number of Clasts (n) | Average dip (degrees) | Eigenvalues | | | Isotropy Index | Elongation Index |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | $S_1$ | $S_2$ | $S_3$ | | |
| 1 | 1 | 157/337 | 5.0 | (NS) | 51 | 19 | 0.4621 | 0.4016 | 0.1361 | 0.2946 | 0.1307 |
| 1 | 2 | 179/359 | 63.2 | >99.9 | 55 | 26 | 0.6307 | 0.2438 | 0.1253 | 0.1986 | 0.6133 |
| 2(U) | 4 | 014/194 | 30.0 | >99.0 | 54 | 24 | 0.4952 | 0.2908 | 0.2139 | 0.4321 | 0.4127 |
| 3(U) | 8 | - | 14.0 | (NS) | 25** | 42 | 0.4862 | 0.3873 | 0.1263 | 0.2598 | 0.2033 |
| 3(U) | 9 | 144/324 | 41.3 | >99.9 | 56 | 21 | 0.5745 | 0.2627 | 0.1627 | 0.2831 | 0.5427 |
| 3(U) | 10 | 042/222 | 33.7 | >99.0 | 55 | 44 | 0.6228 | 0.2317 | 0.1453 | 0.2334 | 0.6279 |
| 3(U) | 11 | 047/227 | 16.4 | (NS) | 53 | 34 | 0.4724 | 0.3023 | 0.2251 | 0.4766 | 0.3600 |
| 3(U) | 12 | 041/221 | 33.7 | >99.9 | 55 | 25 | 0.5461 | 0.2685 | 0.1853 | 0.3393 | 0.5082 |
| 3(U) | 13 | 103/283 | 16.8 | (NS) | 53 | 34 | 0.4754 | 0.3527 | 0.1607 | 0.3381 | 0.2579 |
| 3(U) | 14 | 143/323 | 18.8 | (NS) | 58 | 38 | 0.4479 | 0.3581 | 0.1938 | 0.4326 | 0.2004 |
| 3(U) | 15 | 158/338 | 21.0 | (NS) | 24** | 24 | 0.4632 | 0.3714 | 0.1652 | 0.3567 | 0.1981 |
| 4 | 17 | 129/309 | 24.8 | >95.0 | 46** | 17 | 0.5518 | 0.3321 | 0.1160 | 0.2101 | 0.3982 |
| 5 | 19 | 023/203 | 41.4 | >99.9 | 53 | 14 | 0.6333 | 0.2662 | 0.1004 | 0.1586 | 0.5796 |
| 6 | 20 | 034/214 | 45.6 | >99.9 | 51 | 25 | 0.5616 | 0.2758 | 0.1625 | 0.2894 | 0.5089 |
| 6 | 21 | 108/288 | 44.0 | >99.9 | 36** | 23 | 0.5606 | 0.2276 | 0.2118 | 0.3779 | 0.5938 |
| 6 | 22 | 005/185 | 21.0 | (NS) | 32** | 24 | 0.4688 | 0.3644 | 0.1668 | 0.3560 | 0.2223 |
| 7 | 23 | 003/183 | 14.0 | (NS) | 47** | 23 | 0.4957 | 0.3389 | 0.1653 | 0.3335 | 0.3162 |
| 7 | 25 | 024/204 | 17.0 | (NS) | 35** | 16 | 0.5198 | 0.3743 | 0.1058 | 0.2035 | 0.2798 |
| 8(M) | 27 | - | 8.9 | (NS) | 58 | 25 | 0.4434 | 0.3896 | 0.1669 | 0.3764 | 0.1212 |
| 10 | 29 | 049/229 | 7.0 | (NS) | 51 | 9.5 | 0.5150 | 0.4364 | 0.0486 | 0.0942 | 0.1526 |
| 10 | 30 | 001/181 | 13.0 | (NS) | 54 | 17 | 0.5048 | 0.3351 | 0.1600 | 0.3169 | 0.3360 |
| 10 | 31 | 030/210 | 11.3 | (NS) | 51 | 20 | 0.4677 | 0.3446 | 0.1875 | 0.4010 | 0.2630 |
| 10 | 32 | 065/245 | 7.2 | (NS) | 53 | 24 | 0.4173 | 0.3932 | 0.1894 | 0.4538 | 0.0577 |

U= Upper till, M= Middle till
(NS) not significant at the 95% level (Curray, 1956).
** samples of less than the recommended 50 clasts

**Table 6.2. Results of macrofabric analyses** *(continued over page).*

| Site No. | Sample No. | Resultant Vector (degrees) | Vector Magnitude (%) | Rayleigh Significance (%) | Number of Clasts (n) | Average dip (degrees) | Eigenvalues | | | Isotropy Index | Elongation Index |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | $S_1$ | $S_2$ | $S_3$ | | |
| 11(M) | 34 | 098/278 | 25.1 | >95.0 | 50 | 24 | 0.4872 | 0.3181 | 0.1945 | 0.3992 | 0.3470 |
| 11(M) | 35 | 122/302 | 7.3 | (NS) | 53 | 13 | 0.5110 | 0.4287 | 0.0603 | 0.1180 | 0.1611 |
| 11(M) | 36 | 140/320 | 28.4 | >99.0 | 55 | 25 | 0.5061 | 0.3155 | 0.1782 | 0.3521 | 0.3766 |
| 16 | 41 | 034/214 | 22.0 | >99.9 | 51 | 35 | 0.4844 | 0.2913 | 0.2241 | 0.4627 | 0.3984 |
| 22 | 49 | 162/342 | 24.0 | > 95.0 | 55 | 24 | 0.5051 | 0.3150 | 0.1799 | 0.3094 | 0.2731 |
| 27 | 58 | 061/241 | 9.0 | (NS) | 57 | 24 | 0.4565 | 0.3622 | 0.1811 | 0.3968 | 0.2067 |
| 30 | 63 | 030/210 | 17.5 | (NS) | 50 | 20 | 0.4919 | 0.3604 | 0.1475 | 0.2999 | 0.2673 |
| 30 | 64 | 063/243 | 23.9 | >95.0 | 55 | 21 | 0.5105 | 0.3201 | 0.1692 | 0.3315 | 0.3728 |
| 30 | 65 | 072/252 | 39.6 | >99.9 | 51 | 18 | 0.6222 | 0.2609 | 0.1168 | 0.1877 | 0.5806 |
| 30 | 66 | 091/271 | 29.5 | >99.0 | 50 | 26 | 0.5059 | 0.2939 | 0.2001 | 0.3955 | 0.4190 |
| 30 | 67 | 085/265 | 34.5 | >99.0 | 50 | 23 | 0.5521 | 0.2786 | 0.1691 | 0.3062 | 0.4953 |
| 30 | 68 | 075/255 | 27.2 | >95.0 | 51 | 29 | 0.4771 | 0.2686 | 0.2542 | 0.5328 | 0.4370 |

U= Upper till, M= Middle till
(NS) not significant at the 95% level (Curray, 1956).
** samples of less than the recommended 50 clasts

**Table 6.2. Results of macrofabric analyses** *(continued from previous page).*

## 6.5 Results

### 6.5.1. Resultant Vectors

The significance of the vector strength can be determined using the Rayleigh test. For practical purposes in the field, usually 50 stones are judged to be sufficient to obtain a representative result (e.g. Lindsay, 1970; Benn & Ringrose, 2001) but others have found 25 to 30 sufficient, e.g. Andrews (1971); Lawson (1979); Bennett *et al.* (1999). For this reason, data are included here from the seven borehole cores (Table 6.2) in which less than 50 clasts met the required criteria (Appendix 1). From these seven samples, two – sample 17 (n = 46) and sample 21 (n = 36) - yielded resultant vectors significant at the 95% level or higher (Curray, 1956). The remaining five (samples 15, 8, 22, 23 & 25) did not show statistically significant orientation of clast a-axes. It may well be the case that if further clasts had been available for measurement, a significant result would have been obtained.

### 6.5.2. Eigenanalyses

In order to investigate fabric shapes (Section 6.4 - Objective 5), the macrofabric data shown in Table 6.2 were plotted on Figures 6.1 and 6.2. Figure 6.1 shows the primary ($S_1$) eigenvalues to range from 0.417 to 0.633 representing a moderate to high degree of clustering, the tertiary ($S_3$) eigenvalues ranging from 0.048 to 0.254. Figure 6.2 shows two of the samples (29 and 35) from Sites 10 and 11 possess girdle-type fabrics. This is confirmed by the macrofabric diagrams shown in Section 5.2 (Figures 5.46 & 5.54). The remaining samples appear to lie in the central region of the Benn diagram (Figure 6.2), showing no tendency towards isotropic, girdle or cluster distributions.

### 6.5.3. Comparison with previous work

Before the mid-1990s it was generally considered that the Lowestoft Till was for the most part a lodgement till (Whiteman, 2002). Exceptions, usually of restricted lateral extent, include the slumped, flow and sheared tills featured in Figures 6.4 and 6.5. Following the development of the deforming bed model based on studies of modern glaciers, it has been suggested that large tracts of Lowestoft Till, where resting on soft substrate, are composed of deformation tills (Hart *et al.*, 1990; Hart, 1995; Fish, 2000). However, it is more likely that, as

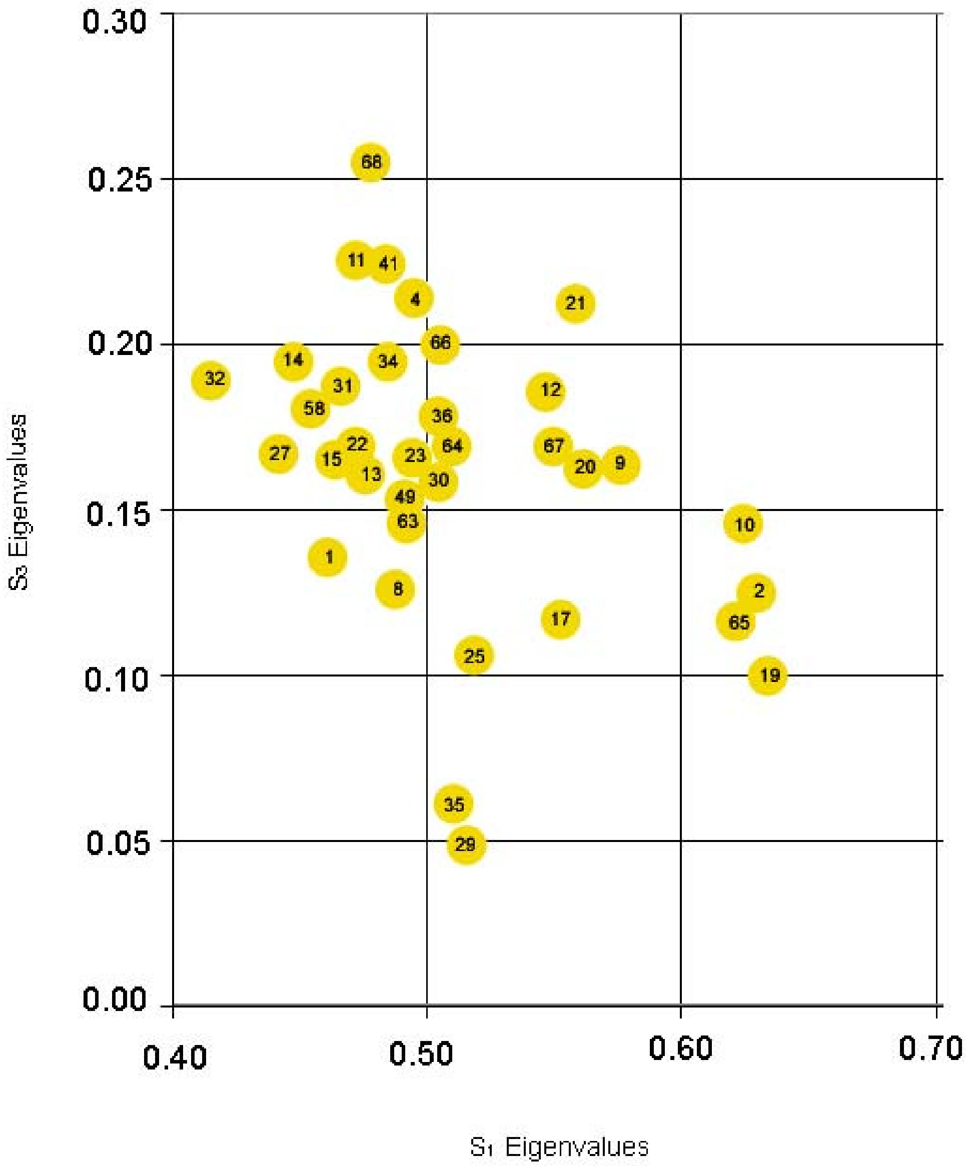


**Figure 6.1. Plot of $S_3/S_1$ eigenvalues.**
(Sample numbers shown – See Table 6.1. for location)

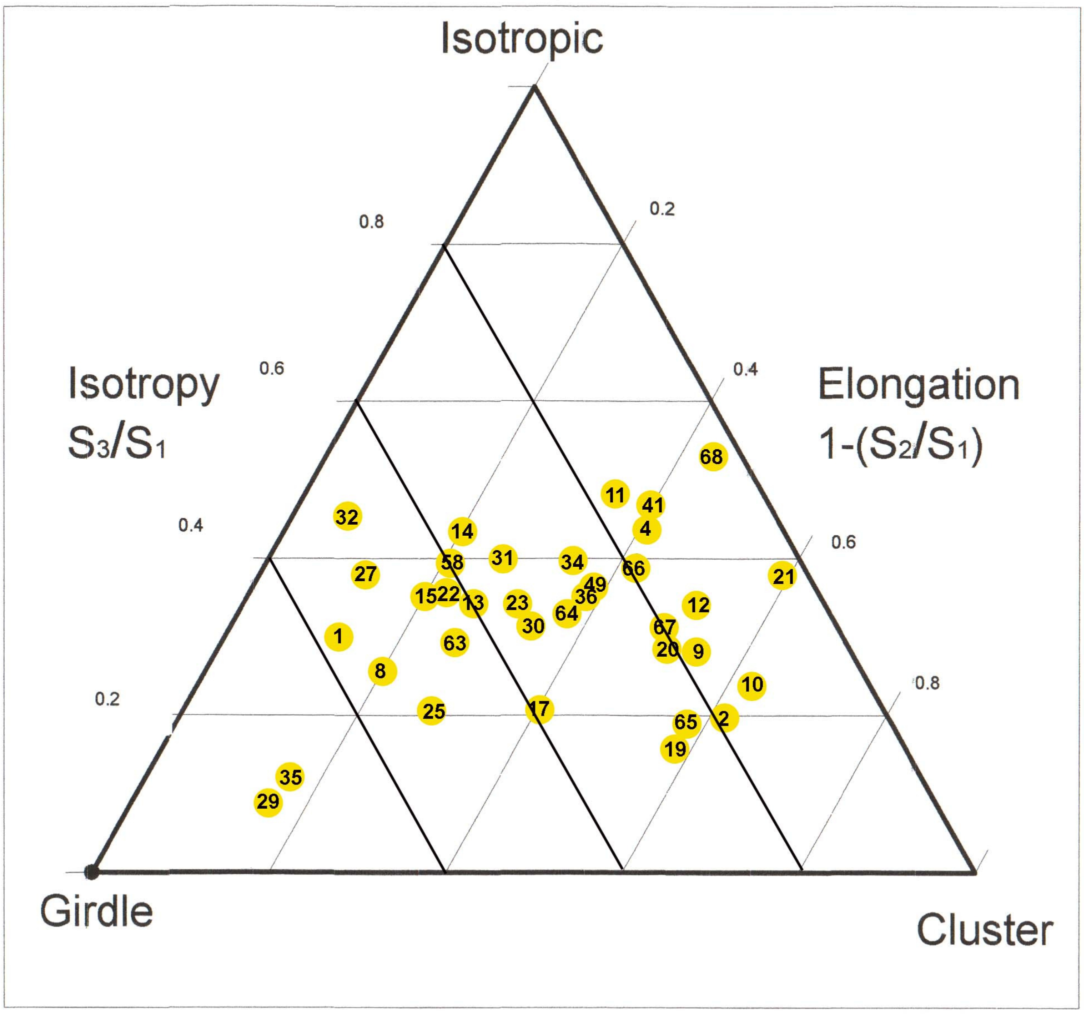


**Figure 6.2.**
**Macrofabric data plotted on ternary (Benn) diagram.**
(Sample Numbers shown)

suggested by Evans *et al.* (2006), a continuum of processes exists, the end members being the classic lodgement till of Boulton (1971) and the heavily modified deformation tills described by Hart (1995).

Figure 6.3 is the bivariate eigenvalue plot of the data shown in Figure 6.1 overlain by process fields obtained from studies of modern glaciers (after Dowdeswell & Sharp, 1986). The field relating to “deformed lodgement till” is based on data from deformation horizons above subglacial lodgement tills reported at Breidamerkurjökull by Boulton & Jones (1979). This may represent only one part of the lodgement – deformation continuum described above, whereas deformation tills such as that at Barrington (Fish, 2000) shown in Figure 6.5, extend the field shown in Figure 6.3. to lower values of $S_3$. To avoid confusion, no distinction has been made in this study between deformed lodgement till and deformation till. The field describing melt-out till in Figure 6.3 is not representative of the Pleistocene data reported by Hart (1998) which featured lower (<0.5) $S_1$ and higher (>0.1) $S_3$ values.

To enable direct comparison with other examples of the Lowestoft till, data from previous work were subjected to eigenanalysis and are shown overlain on data from the current study in Figures 6.4 and 6.5. Data relating to four Hertfordshire lodgement tills were kindly supplied by Dr. D.A. Cheshire and are shown in Figure 6.4 together with examples of lodgement and slumped till from south Hertfordshire (Rose, 1974). Figure 6.5 illustrates fabrics from units 12 and 15 at Site 11 (Primrose Hill Quarry, see Section 5.2) obtained during previous studies by Etienne (2001) and the writer (Brownsell, 1996), together with data from deformation tills found to the east of the study area at Barrington (Fish, 2000). Also shown for comparison are examples from Allen *et al.*, (1991) of lodgement till (Blakenham Member), flow till (Creeting Hill Member), a slumped melt-out till (Bramford Member) and a further sheared and deformed till (Broomwalk Member) from Suffolk. The aforementioned Bramford member was believed to have undergone loss of fine material during melt-out, but the fabrics were considered to be the result of slumping (Allen *et al.* 1991).

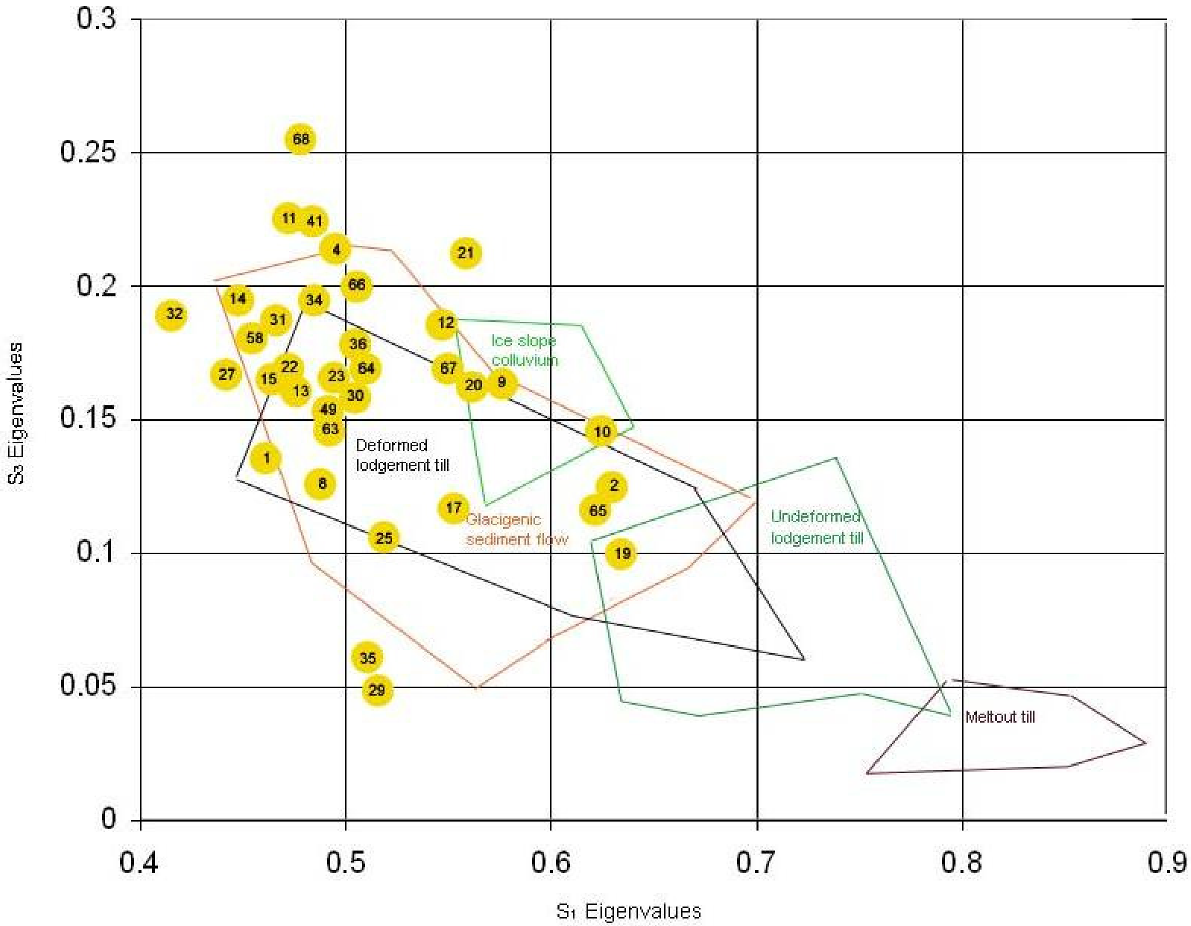


**Figure 6.3. Data from the present study overlain by process fields obtained from modern glaciers** (after Dowdeswell & Sharp, 1986).

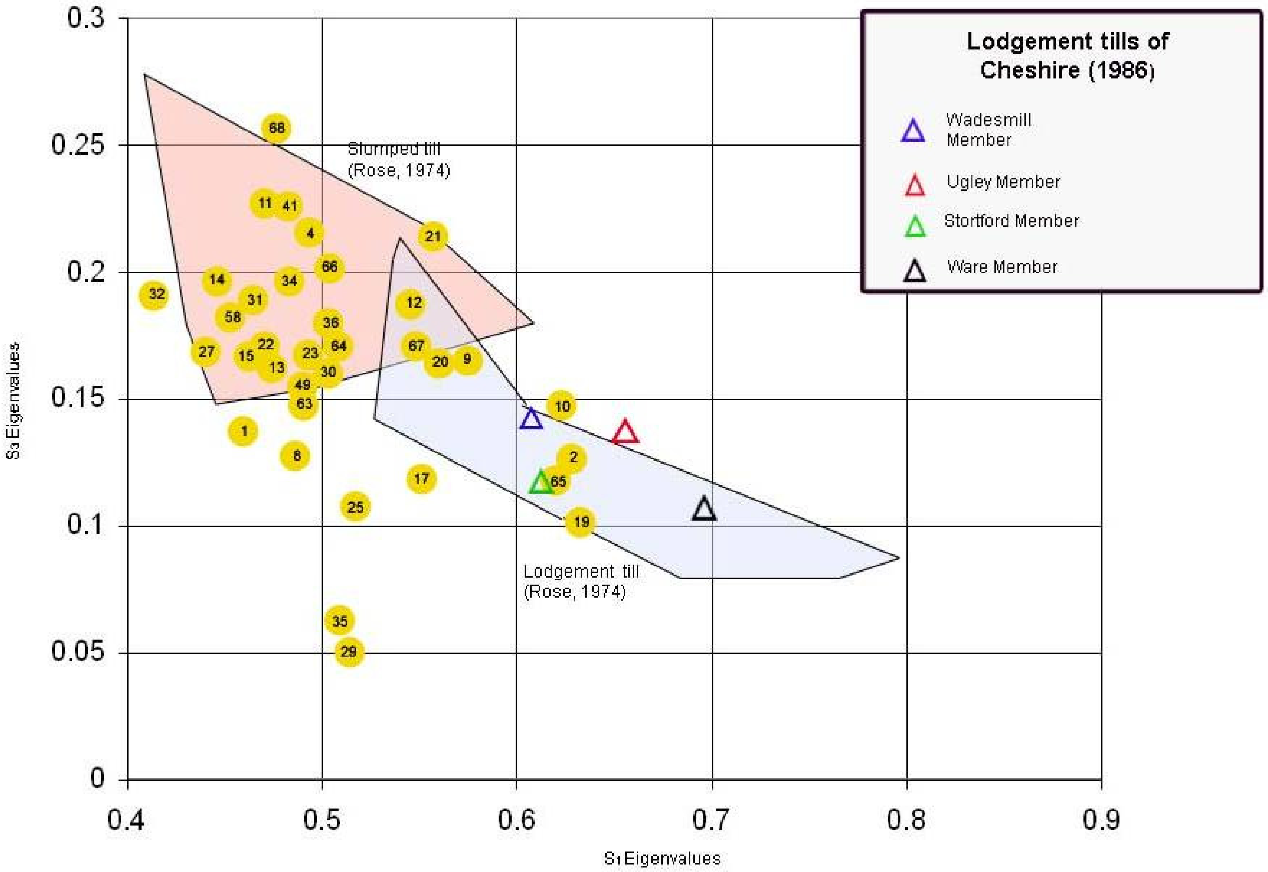


**Figure 6.4. Data from Hertfordshire Tills .**
(Data from current study shown for comparison)

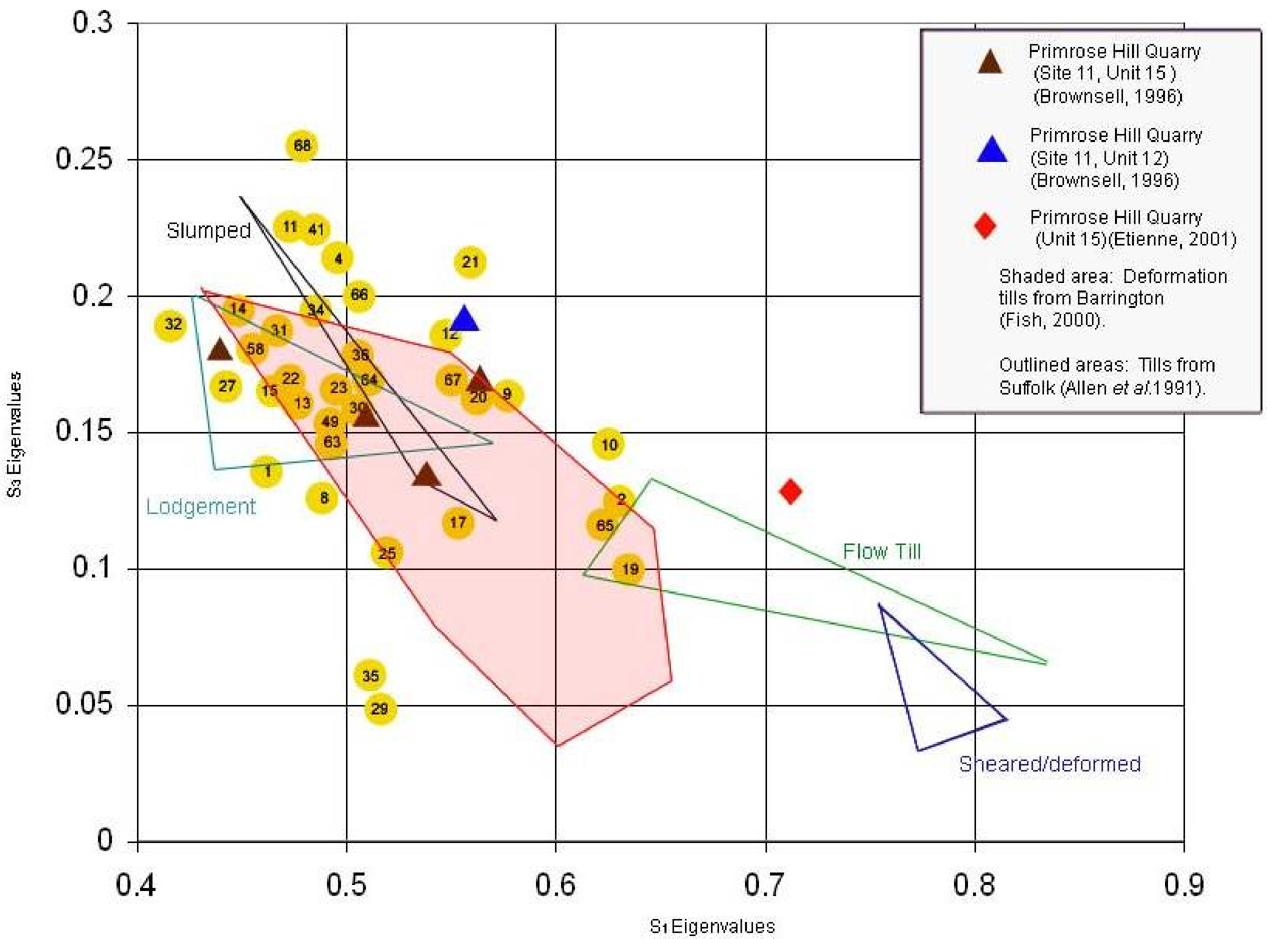


**Figure 6.5. Data from Primrose Hill Quarry (Brownsell, 1996; Etienne, 2001), Barrington (Fish, 2000) & Suffolk (Allen *et al.*, 1991).**
(Data from current study shown for comparison).

Examination of Figures 6.3 to 6.5 shows the position of many samples from the current study to correspond to different fields, e.g. sample 58 from Site 27 lies within the glacigenic sediment flow field of Figure 6.3, the slumped till field in Figure 6.4 and within both the lodgement and deformation till fields in Figure 6.5. Thus, comparison of these three figures clearly shows a conflict between the areas suggested to be related to different types of till. In particular the areas relating to (undeformed) lodgement till are widely spread with $S_1$ eigenvalues ranging between ~0.43 and ~0.79. Also, many of the lodgement tills of Brownsell (1996), Allen *et al.* (1991) and the Stortford and Wadesmill Members of Cheshire (1986) overlap the field relating to the deformation tills from Barrington. The slumped till in Figure 6.4 was identified as such by Rose (1974) on the basis of a relatively variable energy environment suggested by a wide range of vector magnitudes (4% - 46%), high clast dip (average $34^{o}$) and a random distribution of sedimentary properties. The envelope relating to this till overlaps that of the slumped till of Suffolk (Figure 6.5), although the latter extends to lower $S_3$ values.

It appears, therefore, that such a graph cannot be relied upon as a guide to till genesis. Criticism of the use of eigenanalysis in the identification of till genesis is made by Catto (1998) and Bennett *et al.* (1999). Indeed, Catto (1998) has found considerable lateral variation in till fabrics, with primary eigenvalues ranging from 0.472 to 0.922 within a 12 m distance. Dowdeswell and Sharp (1986) warn "it should not be assumed that a single fabric collected in isolation, or even a small number of fabrics, will necessarily be indicative of sediment genesis". Li *et al.* (2006) also consider further study is necessary before fabric parameters can be used in the reconstruction of the sedimentary history of a deposit.

In view of the above, no further comparisons are made with the fields shown in Figure 6.3. However, in Figures 6.4 and 6.5 comparisons are made with examples of Lowestoft Till from East Anglia for some of which, e.g. Cheshire's tills of Hertfordshire (Figure 6.4) and those from Site 11 of this study (Figure 6.5), detailed lithological and textural descriptions are available. These are considered more appropriate for this study and are considered further. The following section discusses each sample in turn, taking into consideration the results from the macrofabric analysis in conjunction with properties of tills described in Chapters 5 and 7.

## 6.6. Discussion and Interpretation

### 6.6.1. Sites south of Hitchin

Nineteen macrofabrics were obtained from Sites 1 to 7, south of Hitchin, nine of which proved to be statistically significant. Five of these from Sites 2, 3 and 5 lie within the Hitchin Channel and two from Site 6 are found within the Stevenage Channel. The remaining two from Sites 1 and 4 are located outside the channels.

Sites where tills were subjected to macrofabric analyses are shown in Figure 6.6 and resultant vectors of fabrics whose clast alignments reach the 95% confidence level of significance are indicated. Results from Site 11 within the channel north of Hitchin, are shown for completeness.

**Site 1 – Knebworth Park**

Site 1 is the southernmost site in this study. The lower sample (sample 1) from 102.3 m O.D. at Site 1 possesses a very weak fabric with vector magnitude of 5%, low dip values (average $19^{o}$) and no significant preferred orientation. Having a low primary eigenvalue, it plots at a distance from the upper till (sample 2) at this site on Figure 6.1. This sample lies outside all envelopes for comparison tills in Figures 6.4 and 6.5 although it lies near to the lodgement tills of Allen *et al.* 1991. The low vector magnitude and dip values, together with a lower proportion of fines (Section 7.4.1), suggest this is a melt-out till. It could have been deposited by an advance prior to that represented by sample 2 or it may have been deposited by stagnant ice below an active ice layer.

Sample 2 from the upper till at this site at 104.2 m O.D exhibits characteristics very similar to those found in the tills studied by Cheshire (1986). Specifically, Figure 6.4 shows that the eigenvalues for this sample lie very close to those of Stortford and Wadesmill Members from east and south of the study area. However, this similarity is not reflected in the textural characteristics or lithology of these samples (Section 7.5). Sample 2 has one of the highest vector magnitudes found in this study (63.2%) and the highly significant fabric shows

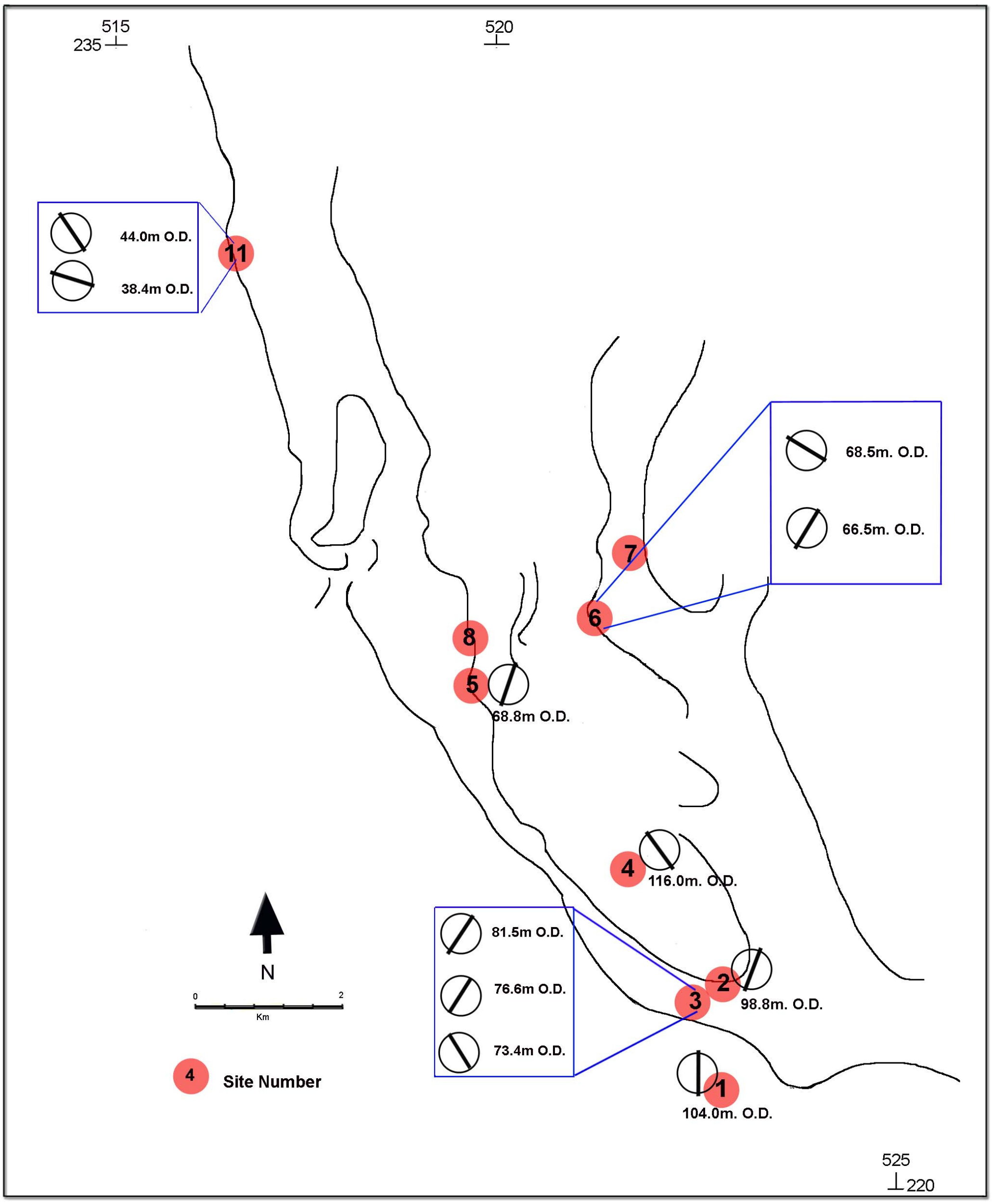


**Figure 6.6. Statistically significant macrofabrics at sites within the Hitchin Gap.**
(channel outlines as depicted on BGS 1:50,000 Sheet 221)

clasts to be strongly aligned in a north-south direction. Over 73% of the dip values in this sample lie below 35 $^{o}$ (Figure 5.4), the average being 26$^{o}$. It lies within the zone depicting the lodgement till of Rose (1974) in Figure 6.4 and in Figure 6.5 it lies on the boundary of the field of deformation tills from Barrington. Given the high vector magnitude and consistent low dips this till probably reflects a relatively undeformed lodgement till and it is likely that the resultant vector reflects the path of ice flow across the site in a north-south direction (Figure 6.6).

**Site 2. (Upper Till) – Norton Green**

At a slightly lower height (98.8 m O.D.) to the north and within the Hitchin Channel, the fabric in sample 4, recorded a similar north-south orientation (significance > 99.0%) to the upper macrofabric at Knebworth Park, with a vector magnitude of 30% and average dip of 24$^{o}$. However, this sample has a high $S_3$ value and plots close to the slumped tills from Suffolk (Figure 6.5) and within the field of slumped tills of Rose (1974) in Figure 6.4, although mean dip values are lower than those recorded by Rose (1974) in Hatfield. The suggestion that this till is a slumped or flow till is supported by particle size analysis in Section 7.4.1, which shows this sample to possess the lowest amount of fine material (< 4.5 phi) found within the Hitchin Channel. This would suggest the removal of such fine material by flowing water during or after deposition. Although the resultant vector of the sample roughly agrees with that found at Site 1, it could represent fabric modification in a remobilised till.

**Site 3 – Cannocks Wood**

Of the eight macrofabrics (samples 8 - 15) investigated at this site, three significant resultant vectors in samples 9, 10 and 12, have been obtained from what appears to be one continuous stratigraphic unit. The lowest fabric (sample 8) at 70.4 m O.D., was based on only 25 clasts and records a weak fabric with vector magnitude of 14%. Above this, sample 9 at 73.4 m O.D. is strongly oriented (significance > 99.9%) in a northwest - southeasterly direction, roughly following the direction of the Hitchin Channel. The direction of the resultant vector goes through an abrupt rotation of 100$^{o}$ above ~ 74 m O.D. with sample 10 at 76.6 m O.D possessing a strong northeast-southwest orientation (significance >99.0%). This is separated from a further strong fabric in sample 12 at 81.5 m O.D continuing the northeast-southwest trend, by a weaker fabric in sample 11 (vector magnitude 16.4%) which, although not significant, also agrees with the fabrics in the samples above and below. Above 83.6 m O.D. clasts are weakly oriented (vector magnitudes between 16.8% and 21%) with non-significant resultant vectors.

Generally the characteristics of the eight fabrics sampled in this unit are rather variable. Vector magnitudes range between 14% and 41.3% and dip values are generally high, ranging from $21^{o}$ to $44^{o}$ with an average of $33^{o}$. These variable fabric strengths and resultant vectors indicate deposition by a process other than lodgement. It is possible that this till was deposited from stagnant ice trapped within the Hitchin Channel. Simple melt-out is unlikely due to the high dip values. However, the base of the Hitchin Channel is believed to slope at this location, suggesting the possibility of a slumped or flow till. In Figure 6.5 samples 8 – 12 plot outside all fields, whilst samples 13 – 15 plot within both the fields of deformation and lodgement till. The highest five of the eight samples at this site (11-15) plot within the field of the slumped till samples from Hatfield (Figure 6.4). Rose (1974) found rapid vertical variation in the Hatfield slumped till with vector magnitudes ranging from 4% to 46% and dip values ranging between $26^{o}$ to $44^{o}$. Values for Site 3 vary between 14.0% and 41.3% and $21^{o}$ and $44^{o}$, respectively. Lawson (1979) found flow till deposits to be characterised by a large scatter of orientations, with primary eigenvalues ranging from 0.490 to 0.700. These values are affected by the water content of the matrix, a higher content being associated with stronger fabrics so that $S_1$ increases accordingly. These samples do not appear to have undergone depletion of fine material (Section 7.4.1), nor do they exhibit high $S_1$ values, therefore a relatively low water content of the matrix is indicated. Fabrics created in a flow/slumped till are unlikely to represent the direction of ice flow (Boulton, 1971).

**Site 4 – Letchmore**

The single sample of till (sample 17) from Site 4, lying on high ground (116.0 m O.D.) between the two channels, has a significant fabric aligned in a northwest/southeast direction parallel to the course of the Hitchin Channel. Low dip values are displayed at this site, with an average of $17^{o}$, suggesting the clasts were subjected to a relatively high stress regime. In Figure 6.5 this sample plots close to the slumped till of Suffolk, but the low dip values mitigate against this mode of formation. However, Figure 6.4 shows this sample plots close to the lodgement till field of Hertfordshire, and it seems likely that this is a lodgement till that perhaps has undergone some minor deformation. It is possible therefore, that the resultant vector represents the general pattern of ice flow.

**Site 5 - St Ibbs**

A macrofabric from only one sample (19) was available from this site. This sample possessed one of the lowest average dips ($14^o$) in this study and records a highly significant NNE/SSW oriented fabric. It lies within the field of lodgement in Figure 6.4 but within both the fields of flow till of Suffolk and deformation tills from Barrington in Figure 6.5. The latter tills were interpreted by Fish (2000) using eigenvalue data but had previously been interpreted by Hoare & Connell (1981) as lodgement till. Low average dip values and a highly significant resultant vector are typical of the classic lodgement process (Boulton, 1971; Mark, 1974) suggesting this is a lodgement till.

**Site 6 – Little Wymondley**

Two of the three fabrics from Site 6 (samples 20 & 21) at Little Wymondley within the Stevenage Channel at 66.5 and 68.5 m O.D. respectively, are highly significant although the two directions are separated by $74^o$. The lowest fabric (sample 20) is aligned northeast/southwest and the upper (sample 21) is aligned WNW/ESE. A further fabric (sample 22) at 70.5 m O.D. based on measurements of only 32 clasts, exhibits a non-significant resultant vector (vector magnitude 21%) in a roughly similar direction to the lowest sample. All three of these fabrics have average dips between $23^o$ and $25^o$.

The three samples, although widely dispersed, plot close to the deformed tills at Barrington, lodgement tills of Suffolk and samples from both tills found at Primrose Hill Quarry (Figure 6.5). They all lie within or very close to the field of slumped till of Rose (1974) in Figure 6.4. The two lower samples (20 & 21) have similar vector magnitudes at 45.6% and 44.0%, respectively, indicating a consistent stress regime. It is suggested that this is a deformation till. The presence of two strong fabrics at the base may indicate this unit is comparable to the two horizons of deformation till recorded by Hart *et al.* (1990). A lower layer of more compact, stiff till is overlain by a more dilatant till represented by sample 22 with resulting weaker fabric (vector magnitude of 21%). The lower fabric at 66.5 m O.D. is likely to record the approximate north-south direction of ice flow moving down the channel whilst the fabric from 68.5 m O.D. may suggest the presence of a transverse component set up in response to compression created within the ice as it encounters the walls of the narrowing channel.

**Site 7 – Great Wymondley**

Two weak fabrics (vector magnitudes less than 20%) from 81.5 m (sample 23) and 85.5 m O.D. (sample 25) were obtained from Site 7 within the Stevenage Channel, where less than 50 clasts were measured. In neither of these samples did the orientation of particle a-axes differ from random at the 95% significance level. The samples possess similar $S_1$ but different $S_3$ values, indicating very different fabric patterns. This is evident from examination of the fabric scatterplots in Section 5.2. Sample 23 has similar eigenvalue characteristics to the slumped till at Hatfield (Figure 6.4) and plots close to the till from unit 15 (Brownsell, 1996) at Primrose Hill Quarry (Site 11) (Figure 6.5). It also coincides with the field relating to the deformation tills of Barrington, and lodgement tills of Suffolk in Figure 6.5. Vector magnitudes and dips are low in both samples, suggesting this is a deformation till, although the two samples clearly have different strain histories. However, sample 25 from 85.5 m O.D. has a much lower $S_3$ value and plots outside the fields shown in Figure 6.4 and on the margin of the deformed till in Figure 6.5. This upper sample has one of the lowest average dips ($16^o$) and is shown in Section 7.4.1 to be depleted in fine material, both of which suggest the presence of flowing water during deposition and the possibility that this is a flow till. Despite these characteristics, this sample does not plot near the field of flow till shown in Figure 6.5. Although not significant, the fabrics in both of these samples are also in sympathy with the north-south ice trajectory seen at Site 1.

**Site 8 - St Ippollitts**

The borehole sample (sample 27) at Site 8 on the edge of the Hitchin Channel was not oriented at the time of extraction. However, a very weak fabric was evident with a vector magnitude of 8.9% with dip values averaging $25^o$. Although this sample falls within the envelope of the lodgement till of Suffolk (Figure 6.5), it does not lie close to the lodgement till in Figure 6.4, instead falling within the field of slumped till in this figure. Dip values are extremely variable, ranging between 0° and 72°, although the average of 25° falls within the range found by Rose (1974) to correspond to lodgement till. This probably represents a deformation till, although the position of this site on the margin of the Hitchin Channel suggests slumping against the side of the channel is a possibility.

### 6.6.2. Sites north of Hitchin

Nine macrofabrics were taken from sites north of Hitchin and on the Northeastern Plateau, Sites 10 (Baldock), 11 (Primrose Hill Quarry),16 (Moggerhanger) and 22 (Cockayne Hatley), only four of which were found to be statistically significant. Resultant vectors for sites north of Hitchin are shown in Figure 6.7.

**Site 10 – Baldock**

A series of very weak fabrics with vector magnitudes of between 7% and 13% were recorded in samples 29 - 32 at Baldock with no significant clast alignment. These four samples lying between 66.8 and 70.7 m O.D. possess extremely low dip values. These become progressively steeper from 9.5° at the base to 24°at the top. Similar increasing dip values were considered by Rose (1974) to imply diminishing stress during deposition. It is possible that as stresses decrease, clasts are freer to rotate in any direction, thus increasing the average value of dip, although this has not been reported elsewhere. However, in all the samples these vectors roughly agree with a north-south to northeast –southwest alignment. Above 68.1 m O.D. (sample 30) the vectors change from north-south at the base through northeast-southwest to approximately ENE/WSW at the top.

The till at this site is interpreted here as a deformation till. Three of the four samples (samples 30 to 32) are shown in Figure 6.5 to plot close to the samples from unit 15 (Brownsell, 1996) of Primrose Hill Quarry (Site 11) and their position in Figure 6.4 is within or close to the field of slumped till at Hatfield. Both samples 30 and 31 also show similar characteristics to the till from Barrington and lodgement tills of Suffolk (Figure 6.5). Sample 32 has the lowest $S_1$ value in this study (0.4173). Interestingly, the lowest sample at this site (sample 29) lies away from all other samples on Figures 6.1 to 6.5 with the exception of sample 35 from Site 11.

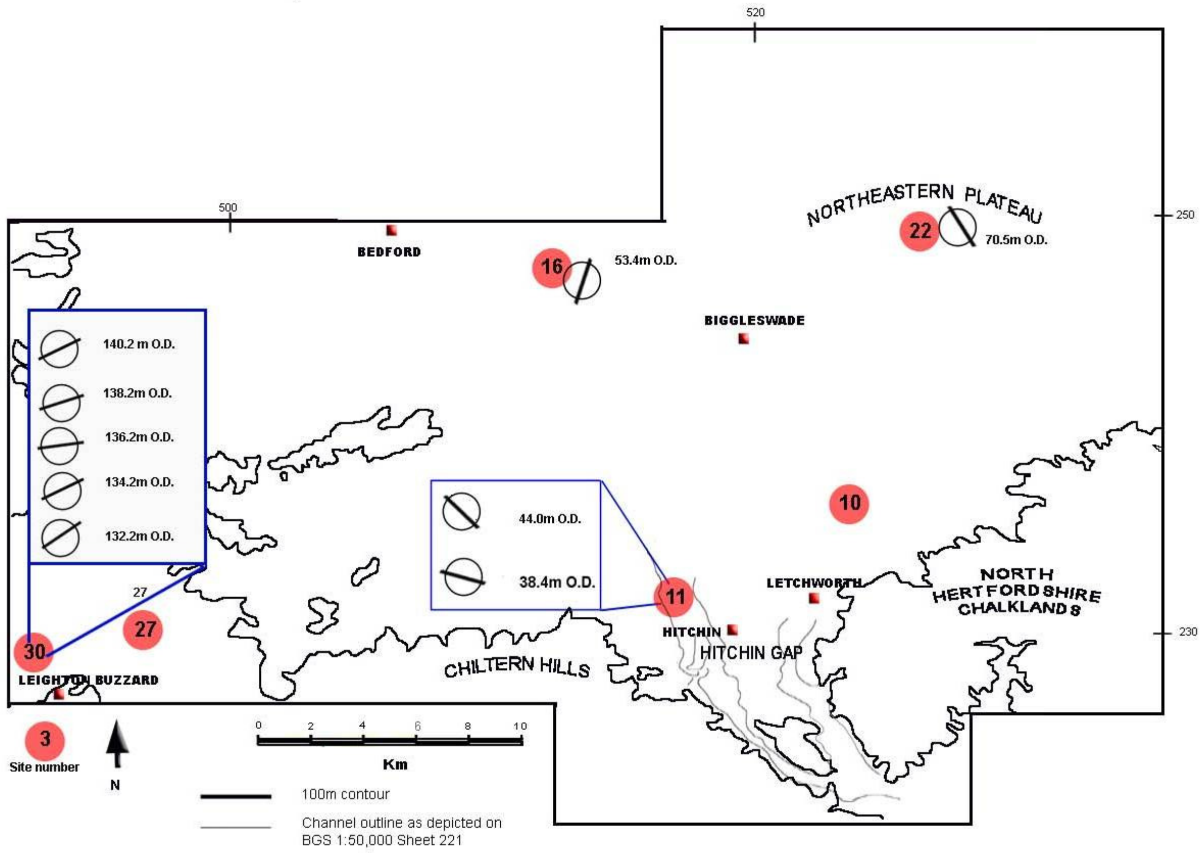


**Figure 6.7. Statistically significant macrofabrics at sites north and west of Hitchin.**

The position of these two samples on the Benn diagram (Figure 6.2) indicates girdle-like fabrics, shown in the scatterplot in Section 5.2, but not seen in the other samples. Sample 29 possesses the lowest dip values measured in this study (9.5°). The data in Table 6.2 show that this sample, at 66.8 m O.D., does not continue the pattern exhibited by the remaining samples from this site. Between 68.1 m and 70.7 m O.D., the primary eigenvalues and the vector magnitudes decrease systematically. However, sample 29 has a vector magnitude of 7%, similar to that found in the highest sample (sample 32). Other similarities between the highest and lowest sample at this site are also noted in Section 7.4.4, where the textural characteristics suggest folding or rafting of these sediments. Possible deformation (?shearing) in the lower levels of this till is indicated by numerous chalk stringers seen above the base of the section (Section 5.2).

**Site 11 – Primrose Hill Quarry**

Lying 8.5 km to the west of Site 10, in the mouth of the Hitchin Gap, two significant fabrics are found in two samples from this quarry. Sample 34 from unit 8 and sample 36 from unit 10, together with the data from past studies of units 15 and 12 at this site, are found within and adjacent to the field depicting the deformation tills at Barrington and the slumped tills of Suffolk (Figure 6.5). The significant vector in sample 34 at 38.4 m O.D. and highly significant vector in sample 36 at 44.0 m O.D. indicate clast alignment between WNW/ESE at the base of the section and northwest-southeast at the top. A further sample (35) from unit 10 just below sample 36 at 41.0 m O.D., showed a weak orientation in sympathy with that of the other samples, i.e. 122/302$^{o}$ and may record a transitional fabric. Like sample 29 from Baldock (Site 10), sample 35 lies a distance away from the other data obtained during this study (Figure 6.2), exhibiting distinctive girdle-type characteristics with low dip values.

Samples 34 - 36 (Units 8 and 10) are relatively depleted in finer material (< 4.5 phi – Section 7.4.1), which may indicate the presence of flowing water during or after deposition, suggesting the possibility that this may be a flow till and the macrofabric characteristics of sample 35 suggest a process other than lodgement.

It is possible that units 8 and 10 at Site 11 have undergone some degree of flow, although they have relatively low average clast dips. A degree of sorting by running water is also suggested by the presence of a band of sandy silt present between samples 34 and 35. Thus, the low dips and strong consistent vectors point to this deposit being a deformation till, although some factors suggest an alternative interpretation as a flow till.

**Site 16 – Moggerhanger**

This site is positioned on a southeast facing slope and the fabric may have been subjected to post-depositional flow or slumping and thus may not give a true reflection of clast alignment within the ice. The single sample (sample 41) has a vector magnitude of 22%, the resultant vector showing clast a-axes to be oriented in a northeast-southwest direction. Dip values range between 1$^{o}$ and 88°, many being in excess of 50° (average 35°). It plots within the field of slumped till at Hertford (Figure 6.4) and close to that of Suffolk (Figure 6.5). A lack of fine particles (+4.5 phi – Section 7.4.1.) also suggests this to be a slumped or flow till. Thus, the significant clast a-axis may not represent ice flow direction, but rather it may represent a local gravity flow, although it does appear to coincide with the expected direction of approach from the northeast.

**Site 22 – Cockayne Hatley**

The single sample (49) is of a till with a moderately strong fabric (vector magnitude 24%) yielded a resultant vector of 161/341$^{o}$ (significant at the 95% confidence level) with an average dip value of 24$^{o}$.

This sample was taken from the top of an extremely thick layer of till (~25 m) possibly representing final deposition above the Hatley Channel (Section 5.5). In Figure 6.4 this sample is found close to the bottom of the field of slumped till. It plots both within the fields of lodgement till and deformation till from Barrington (Figure 6.5), in approximately the same position as sample 30 from Site 10 (Baldock) and as Unit 15 (Brownsell, 1996) from Site 11 (Primrose Hill Quarry). It is therefore is interpreted as a lodgement till that may have undergone minor deformation.

**6.6.3. Sites in the western part of the study area**

A total of seven macrofabrics from Sites 27 (Milton Bryan) and 30 (Heath and Reach) yielded five significant resultant vectors.

### Site 27 – Milton Bryan

A very weak fabric (vector magnitude 9%) with non-significant clast orientation, is found in sample 58 from Site 27. The datapoint corresponding to this sample lies within the envelope of lodgement till of Suffolk and just inside the field representing the Barrington deformation tills (Figure 6.5). It also plots within the envelope representing the slumped till of Hatfield (Figure 6.4), but slumped or flow tills were noted by Rose (1974) to have high dip values, whereas although extremely variable, the average at this site is 24$^{o}$. Sample 58 has similar characteristics to samples 30 and 31 from Site 10 (Baldock) and the samples from unit 15 (Brownsell, 1996) at Site 11 (Primrose Hill Quarry) (Figure 6.5). Tills at Site 10 are interpreted as deformation tills and those from Site 11 as deformation or flow tills. Therefore the sample from Site 27 is interpreted as a deformation till. The resultant vector (ENE/WSW), although not significant (vector magnitude 9.0%), is generally in agreement with fabrics obtained from Site 30 lying 5.2 km to the southwest.

### Site 30 – Heath and Reach

Five of the samples (samples 64 - 68) from this site (Table 6.2) have statistically significant resultant vectors and consistently moderate to strong fabrics (vector magnitudes between 23.9% and 34.5%). This till is a homogeneous well compacted deposit, suggesting it has not been subjected to flow or slump processes. Dip values for the lowest four samples range between 18$^{o}$ and 26$^{o}$ which are within those suggested by Rose (1974) for a lodgement till. The resultant vectors follow a clockwise rotation from 063/243$^{o}$ at 132.2 m O.D. to 091/271$^{o}$ at 136.2 m O.D., then anticlockwise through 85/265$^{o}$ to 075/255$^{o}$ at 140.2 m. O.D. The lowest sample (sample 63) has a weaker fabric and a non-significant resultant vector, although the apparent orientation of clasts in a NE/SW direction differs little from the other samples at this site.

The highest (sample 68) possesses the largest $S_3$ value in the study (0.2542) and lies outside the fields shown in Figures 6.4 and 6.5, although plotting close to the slumped till in Figure 6.4. This sample also has higher dip values (average 29$^{o}$) than the other five at this site. It lies within 2 m of the surface and it may have suffered post depositional disturbance, although the resultant vector is similar to the other samples. Samples 63, 64, 66 and 67, lying below

138.2 m O.D, are reasonably tightly grouped with similar characteristics to samples from Primrose Hill Quarry (Site 11) and the deformation tills at Barrington (Figure 6.5). Sample 65 at 134.2 m O.D. has a much higher $S_1$, value, putting it closer to the Stortford Member and within the area of lodgement till of Rose (1974) in Figure 6.4. The consistency of resultant vectors, low dips and position on Figure 6.5 suggest this to be a lodgement till, rather than a slumped till as suggested by Figure 6.4. although sample 68 does appear to have suffered some disturbance.

## 6.7. Discussion

### 6.7.1. Site 11 - Data from the writer's previous research

The tills lying above 52.87 m O.D. at Primrose Hill Quarry (Site 11) were the subject of a previous investigation by the writer. These data, shown in Figure 6.5, are summarised in Table 6.3.

A fabric consistent with an ice advance from the north-northeast was found between 52.87 and 53.32 m O.D. (unit 12) with a vector magnitude of 29% and mean dip of 26.5$^o$. Above this, a massive till was sampled between 63.5 and 70.5 m O.D. and four fabrics were obtained. The lowest of these revealed a relatively strong northeast-southwest alignment of clast a-axes (vector magnitude 44%), above which at 66.5 m O.D. was a very weak fabric (vector magnitude 7%). The upper two samples recorded a north-south oriented fabric with significant and highly significant clast orientations at 68.5 m and 70.5 m O.D. respectively. Dip values were fairly consistent, lying between 20$^o$ and 26.5$^o$ except in the uppermost sample which was much higher at 45.4$^o$. The datapoint relating to the uppermost sample lay very close to the slumped till from Suffolk on Figure 6.5, which may suggest some post-depositional disturbance, this sample being situated within 1.0 m of the ground surface. A single macrofabric obtained by Etienne (2001) described in Section 6.5.3. is shown in Figure 6.5. Although this plots at a distance outside any fields shown in Figures 6.4 and 6.5, with very high primary eigenvalues and widely varying dip values, Etienne interpreted this as a hybrid lodgement/deformation till. This is in agreement with the plots of Brownsell (1996), which do not coincide with the position of Etienne's datapoint, but group around the lodgement and deformation till fields in Figure 6.5.

| Sample code | Dip (degrees) | Resultant vector (degrees) | Vector magnitude (%) | Height (m. O.D.) |
|---|---|---|---|---|
| **Unit 12, Primrose Hill Quarry, Holwell (Site 11)** | | | | |
| PHQL | 26.5 | 24/204 | 29% | 53.32 |
| **Unit 15, Primrose Hill Quarry, Holwell (Site 11)** | | | | |
| PHQU1 | 24 | 54/234 | 44% | 64.5 |
| PHQU2 | 20 | 76/256 (NS) | 7% | 66.5 |
| PHQU3 | 24 | 9/189 | 26 | 68.5 |
| PHQU4 | 45.4 | 177/357 | 31 | 70.5 |

(NS) not significant at the 95% confidence level (Curray, 1956).

**Table 6.3. Data obtained from Primrose Hill Quarry (Site 11) from previous work by Brownsell (1996).**

## 6.8. Till Genesis

In Section 6.6 eight of the fourteen till units are interpreted as tills which may have undergone some degree of deformation. This is in keeping with the views of Hart *et al*. (1990) and Hart (1995) who considered that a large proportion of the till in East Anglia is highly deformed. She notes (1995) that deforming bed conditions are difficult to identify where tills are homogeneous and fabrics can be similar to those of lodgement till. Factors affecting till forming processes include substrate lithology and cohesiveness, sub-till and glacier topography and prevailing substrate porewater pressures. Very few of the samples in this study overlie Chalk bedrock. Most are found above unconsolidated or soft geological formations such as Woburn Sands, Oxford and Gault Clays, or overlie sand and/or gravel units or clays within channel sequences. It is therefore considered possible that many of the deposits studied here may represent deformation till. Evidence of this is found at sites 15 (Southill) and 18 (Warden Street) where large quantities of sand were found to be assimilated into the tills, indicating shearing of the underlying Woburn Sands.

## 6.9. Ice flow trajectories

This section evaluates the evidence for direction of ice flow across the study area and localised variations due to topographic features (Section 6.4 - Objectives 1 & 2). In the previous section various macrofabric and textural properties were used to determine the likely mode of deposition and direction of clast a-axis orientation. This section discusses the likelihood of the fabrics offering an indication of the direction of ice flow across the study area. Fabrics from suitable sites are then described and an attempt made to reconstruct the direction/s of ice advance into the study area.

A single till fabric site may not give a reliable indication of the direction of ice flow. Fabric measurements taken during this study are in the form of 1) single measurements from isolated sites, or 2) multiple measurements from one exposure (or borehole). Although multiple samples at controlled spatial separation might offer improved chances of obtaining a representative fabric, some authors consider the chances of obtaining such to be low (Andrews, 1971; Catto, 1998). Rose (1974) encountered high local variability in till fabrics in south Hertfordshire, and in a study of Scottish tills, Carr & Rose (2003) remarked on the “surprisingly low” number of resultant vectors that were aligned parallel to the direction of ice flow as defined by independent means. This was also the case with the ‘plateau till’ at Great Blakenham (Allen *et al.,* 1991).

Fabrics from within the channel sequences are more likely to reflect local influences. Deposits here are characterised by a wide variety of sediments often of limited lateral and vertical extents. Processes mentioned in Section 6.2 causing disturbance to original till fabrics are more likely to occur in the confines of the channels, where settling and post depositional disturbance is common. As a result fabrics obtained here may not represent the direction of ice movement.

In spite of the above comments, when the fabric data are plotted, a regional direction of ice-flow can be detected, as well as local variations due to changing topography within the channel sequences. These are discussed in detail below.

Resultant vectors are usually assumed to represent ice-flow direction in undeformed lodgement tills (Boulton, 1971; Lawson, 1979). Therefore macrofabrics of the upper sample at Site 1 (Knebworth Park) and at Site 5 (St Ibbs) are believed to provide an indication of ice flow trajectory. Clast orientation is also generally preserved in melt-out tills, although it is usual for a reduction in fabric strength to occur during deposition (Mark, 1974; Lawson, 1979). Thus clast orientation seen in the melt-out till sampled at Site 1 may also indicate ice flow direction. Resultant vectors at Site 30 are also likely to indicate the direction of ice movement, although there is a possibility that a transverse clast orientation is seen at this site (discussed below). Parallel-to-flow clast orientations in deformation tills such as those seen at Sites 4 (Letchmore), 6 (Little Wymondley), 11 (Primrose Hill Quarry) and 22 (Cockayne Hatley) are generally preserved, providing the direction of stress remains unchanged (Evans *et al.,* 2006). No statistically significant vectors were seen in the deformation till at site 10 (Baldock), suggesting a variable stress regime. Glacigenic clast alignment in tills subject to slump or flow processes is likely to be modified accordingly. These tills are seen at Site 2 (Norton Green), Site 3 (Cannocks Wood) and Site 16 (Moggerhanger). Macrofabrics indicate that tills at sites 7 (Great Wymondley), 8 (St Ippollitts) and 27 (Milton Bryan) may also have undergone some degree of slumping. It is uncertain whether substantial modification of these fabrics has occurred, so it is uncertain that the resultant vectors can be related to the direction of ice movement across these sites.

**Hitchin Gap**

Macrofabrics from Sites 1 (Knebworth Park) and 5 (St Ibbs) suggest ice moving into the Hitchin Gap in a north-south direction, whilst fabrics from Sites 4 (Letchmore) and 6 (Little Wymondley) probably indicate influences of the local topography within the channel system. These findings are in agreement with non-significant fabrics at Sites 7(Great Wymondley) and to some extent those at Site 10 (Baldock) outside the Hitchin Gap, although some of the latter probably reflect changes in direction of stress at the base of the Chalk scarp.

In the area north of Hitchin and on the Northeastern Plateau, significant fabrics are found at Sites 11 (Primrose Hill Quarry) and 22 (Cockayne Hatley). The latter records alignment of clasts in a NNW-SSE direction. At Site 11 samples 34 and 36 from units 10 and 8, respectively, record a northwest-southeast to WNW – ESE alignment. However, this site lies within the Hitchin Channel, close to the western wall and the samples were obtained from the middle till from this borehole (Figure 5.51) deep within the channel sequence. The macrofabric may therefore result from deflection of the ice by the channel wall. Two previous macrofabrics obtained by the writer from the upper till at this site (Unit 15, Table 6.3) record an approximate north-south alignment, in agreement with those found by Etienne (2001). This may represent the direction of ice flow above the infilled channel. The general southerly direction of ice movement suggested in this study area roughly agrees with radial flow trajectories from the Wash as suggested by Perrin *et al.* (1979) and Fish (2000).

Till at Site 27 (Milton Bryan) may have undergone some degree of slumping, although the significant resultant vector obtained here is in agreement with those found at Site 30. Southwest of Hitchin, the Chalk scarp formed an insurmountable barrier to the advancing ice sheet. Ice travelling in a roughly NNE/SSW direction entering the central and eastern part of the study area appears to have been deflected southwest to west down the Vale of Aylesbury, giving the northeast-southwest to east-west fabrics seen at Site 30 (Heath and Reach). However, an alternative interpretation of these fabrics is that this part of the study area was over-run by an earlier ice sheet from the northwest as suggested by Baden-Powell (1948), West & Donner (1956) and Rose (1992, 1994 and in Clark *et al.*, 2004; Rose, 2007). The direction of ice movement would have been roughly normal to the scarp, resulting in the build up of compressive stresses within the ice sheet, which have been shown to result in the creation of transverse fabrics (Allen *et al.*,1991). Thus the results of macrofabric analysis at this site may show transverse clast orientations in ice travelling in a southeasterly direction. Non-significant fabrics at Site 27 (Milton Bryan) may be in sympathy with those at Site 30. Both sites occupy a higher elevation than those lying to the east and as such may represent isolated remnants of deposits of such an advance. However, further investigation of till closer to the scarp in the west of the study area is considered necessary before this hypothesis can be developed further.

### 6.10. Comparison with macrofabrics from previous studies

The generalised directions of ice flow suggested by this study are overlain on patterns of ice advance suggested by previous authors, i.e. West and Donner (1956), Rose (1992), Cheshire (1986), Whiteman (1987) and Fish & Whiteman (2001) in Figures 6.8 to 6.11. Ice advance into the Hitchin Gap was topographically controlled and in the west of the study area the directions discussed in Section 6.9 either represent deflection of the ice sheet by the Chalk

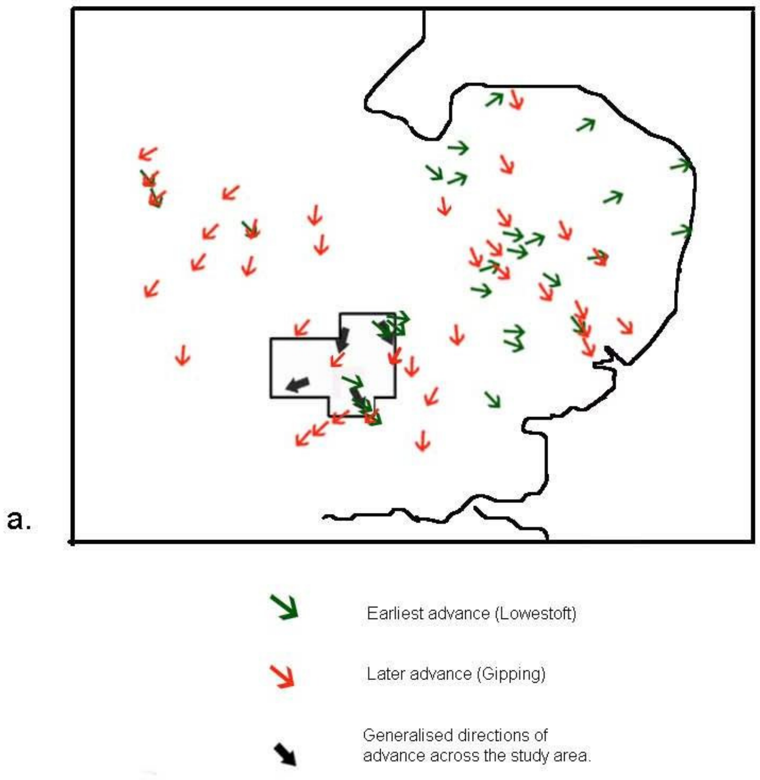


**Figure 6.8.**
Generalised flow directions from current study overlain on patterns of ice flow suggested by West & Donner (1956).

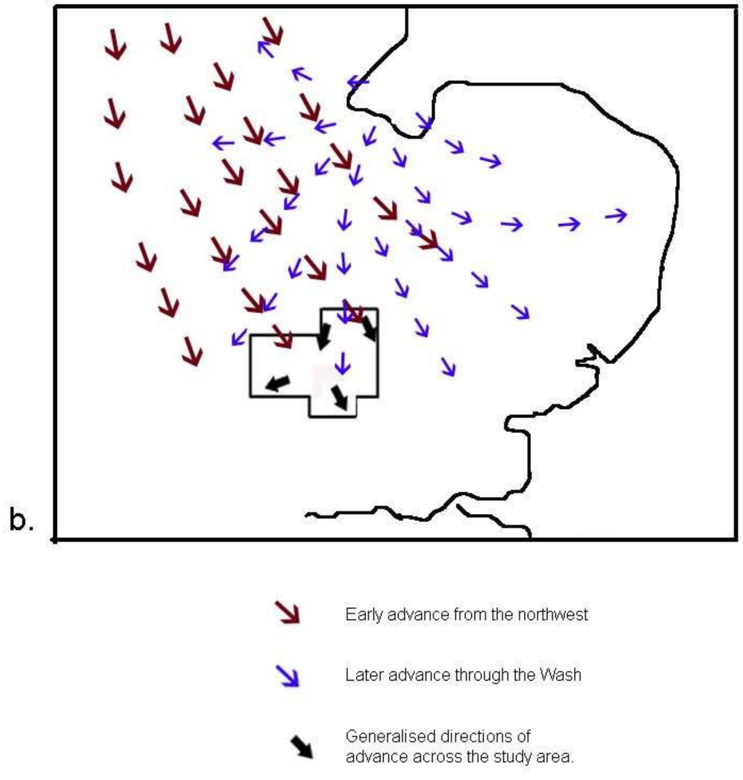


**Figure 6.9.**
Generalised flow directions from current study overlain on patterns of ice flow suggested by Rose (1992).

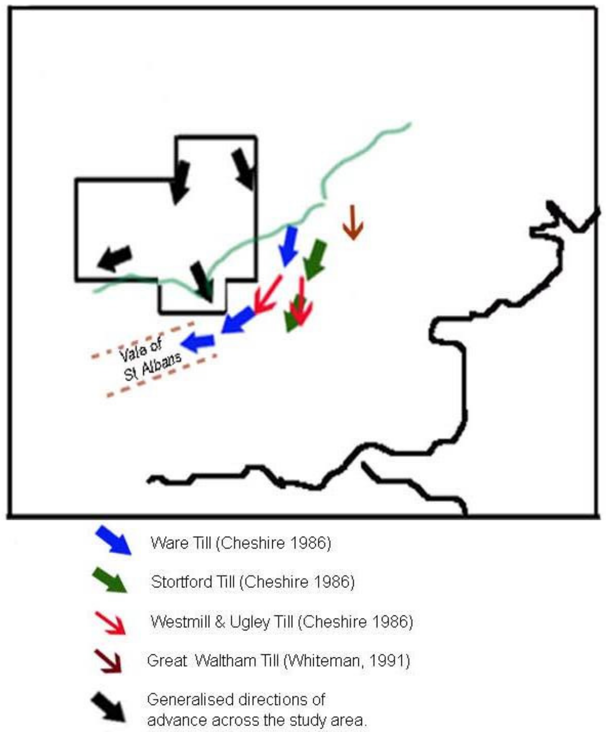


**Figure 6.10**
Comparison of generalised flow directions from current study overlain on patterns of ice flow suggested by Cheshire (1986) and Whiteman (1991).

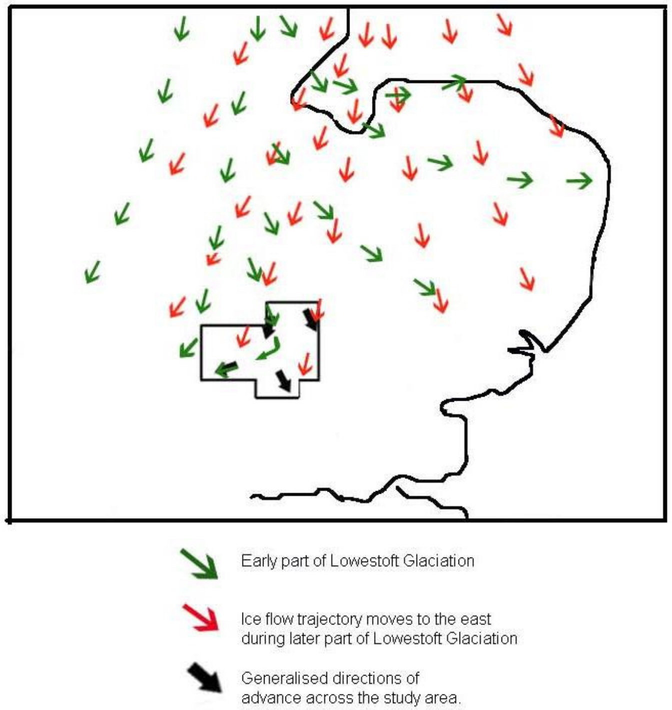


**Figure 6.11**
Comparison of generalised flow directions from current study overlain on patterns of ice flow suggested by Fish & Whiteman (2001).

scarp or compressive stresses present in an ice advance from the northwest-NNW. In both of these cases, the black arrows shown in Figures 6.8 – 6.11 represent localised fabrics and are not expected to agree with the generalised patterns proposed by the above authors.

Despite the above comments, Figure 6.8 shows fabrics at Site 30 (Heath & Reach) appear to agree with the later Gipping advance of West & Donner (1956), as do those at Site 16 (Moggerhanger) although the fabric at this site may have suffered from post-depositional disturbance (Section 6.6.2). However, fabrics from Site 22 (Cockayne Hatley) in the northeast of the study area align better with those of the first (Lowestoft) Glaciation. In Figure 6.9 the ice flow trajectories proposed in the second advance suggested by Rose (1992) were identical to those of the single advance of Perrin *et al.* (1979) (Section 3.17.2). Ice flow at Site 22 agrees with the first advance of Rose (1992) from the northwest, whilst the trajectory suggested further west at Site 16 is in better agreement with the second advance (see comments above).

Ice flow patterns shown in Figure 6.10, suggested by Cheshire (1986) and Whiteman (1987), relate to ice movement around the North Hertfordshire Chalklands and into the Vale of St Albans. The controlling influence of topography on ice flow east and south of the study area was noted by Cheshire (1986). Fabrics obtained in the northeastern part of the study area agree with those of the Great Waltham Member of Whiteman (1987) and may well follow directions taken by the Ware Till of Cheshire (1986) as it curved around the high ground before entering the Vale of St Albans.

Fish & Whiteman (2001) suggested a single ice advance from the north, the locus of which moved east over time, from an initial position NNE of the study area. Hence the green arrows in Figure 6.11 represent an early part of the glaciation (lower tills), and the red arrows represent later direction of ice flow (upper tills). Fabrics from this study appear to show better agreement with the ice flow directions during the early part of the advance.

## 6.11. Conclusions

The following summary conclusions of this chapter are related to the achievement of Objectives given in Section 6.4.

The macrofabrics found in deformation and lodgement tills indicated ice moving into the central and eastern parts of the study area from a general NNE to northeasterly direction (Objective 1). Tills in the western part of the study area are likely to have been deposited by the same ice sheet after deflection by the Chalk scarp, or alternatively may provide evidence of a separate advance from a northwest or north-northwesterly direction (Objective 3).

Deposits within the channel sequences include a diverse range of tills including slumped/flow, melt-out, lodgement and deformation tills. Macrofabrics from both the Hitchin and Stevenage Channels show evidence of modification due to encounters with the channel walls (Objective 2).

Eigenanalysis has shown that data obtained from modern glacial environments do not provide a good basis for the interpretation of tills of unknown origin (Objective 4). Bennett *et al*. (1999) were critical of the use of clast fabrics in the determination of till genesis, stating that " clast fabric alone is not able to discriminate between different glacigenic facies". Evans and Heimstra (2005) believe that the signatures of subglacial tills are too complex to allow genetic classification. This study offers some support for these opinions. The clast fabric envelopes for till types are shown in Figures 6.3 to 6.5 rarely plot in the same position, whether the tills are of modern or ancient origin. The field of lodgement tills from Suffolk (Figure 6.5) lie a considerable distance away from that of Hertfordshire lodgement tills in Figure 6.4, and from that of modern glaciers in Figure 6.3.

The results for examples of Lowestoft Till shown here have a more diverse range of characteristics than indicated by the process fields of Figure 6.3. Distinctions between deformation tills, lodgement tills and melt-out tills, although clear in theory, are in practice often ambiguous in the field and open to conflicting interpretations. As a consequence, the comparisons may not be valid in all cases. Further, subglacial sediments may possess very complex and polygenetic histories, each till having unique characteristics which again undermines comparisons.

For these reasons, it is important that the interpretation of tills should be based on a range of different criteria, only one of which is macrofabric analysis.

The methods adopted in this study include the consideration of eigenvalue data, other macrofabric characteristics (i.e. resultant vectors and average dips) together with textural data in order to arrive at one or more suggested correlations and origins for each till investigated. This allows an assessment of a broad range of characteristics, giving a more complete picture of each till.