CHAPTER 4
METHODOLOGY

4.1. Introduction

The methods employed in this study were designed to collect the data required in order to achieve Objectives 3 and 4 in Section 1.1, i.e. to establish a local lithostratigraphic sequence and where possible to correlate major units in this sequence with those in adjacent areas. Till comprises a variety of re-worked sediments and is therefore complex in composition, but possesses distinctive properties which enable the differentiation of separate stratigraphic units (Perrin *et al.,* 1979; Allen *et al.,* 1991). These properties can also provide information on the mode of sediment deposition, ice flow direction and source of sediment supply (Lowe & Walker, 1997), and thus will assist in achieving Objective 5 (Section 1.1).

4.2. Selection of methods

The following is a review of the field and laboratory methods considered in this study. Sections 4.2.1. to 4.2.7. describe methods that were selected, whilst Section 4.2.8. reviews further methods that were rejected for the reasons given. Successful discrimination between till units has been achieved previously by the use of various combinations of particle size, carbonate content and lithological analyses (Madgett & Catt, 1978; Perrin *et al*., 1979; Whiteman, 1987; Allen *et al.,* 1991). Therefore, together with macrofabric analysis, these methods formed the basis of this investigation.

4.2.1. Particle size distribution – sieving and laser diffraction methods

Particle size analysis has proved to be one of the most powerful tools in the interpretation of unconsolidated sediment (Swift *et al.,* 1972) and is a method routinely used in the investigation of glacial deposits (Ehlers, 1996). Knowledge of the particle size distribution is required in order to characterise a till and to assess and explain variations across the study area. It is relatively easy to measure and provides valuable data for correlation and differentiation of till units, as well as perhaps providing evidence of transport history. Sieving of the fraction greater than +4.5 phi has remained a most satisfactory and reliable method for some considerable time and has been used successfully by many workers (Rose, 1974; Madgett & Catt, 1978; Rice, 1981; Whiteman, 1987; Allen *et al.,*

1991). It is essential that new data in the current study can be compared with that acquired by previous workers such as Cheshire (1986), and the use of the sieving method will allow this. The method involved establishing particle size distribution of sieved fractions between -4.5 to +4.0 phi, i.e. sizes ranging from the smallest size particles that can be practically separated by sieving, to the largest size yielding a statistically viable number of clasts. This method also facilitates the measurement of the acid-soluble fraction, described in Section 4.4.4. The selection of certain sieved fractions can allow tight control over the size of clast subjected to small clast lithological analysis.

Analysis of clay and silt fractions led to the successful separation of North Sea Drift from the Lowestoft Tills by Perrin *et al*. (1973). The laser diffraction method offers advantages of speed and replication (McCave *et al.,* 1986). The Mastersizer S used in this study can be used for particles up to 1 mm in diameter but a suitable particle size range of 0.08 to 56.23 μm (approximately +14.0 to +4.2 phi) was considered to complement the sieve analysis described above. An evaluation of this method for natural sediments conducted by Loizeau *et al*. (1994) concluded this to be a time saving method with increased reliability. Therefore this method was selected in preference to the more traditional sedimentation technique which is more time consuming.

4.2.2. Carbonate analysis

Assessment of the carbonate content of the sieved fractions in Section 4.4.4. facilitated calculation of the acid-insoluble element of the particle size distribution. This enabled comparison of tills where local assimilation of Chalk bedrock has to be taken into account, as is the case in the vicinity of the Chalk scarp.

4.2.3. Macrofabric analysis

This is one of the oldest and most popular techniques in the reconstruction of glacial palaeoenvironments (Hambrey, 1994). The method has formed part of many comprehensive investigations into glacial deposits (West & Donner, 1956; Rose, 1974; Gibbard, 1977; Hoare & Connell, 1981; Rice, 1981; Whiteman, 1987; Allen *et al.,* 1991; Etienne, 2001). It has provided much information concerning the direction taken by the Anglian ice sheet as it deposited the Lowestoft Till. Agreement exists between many of the findings of different

workers and the technique appears to be successful. It was considered therefore that, wherever possible, fabric data would be collected from sites investigated during this study. This included data collected from oriented borehole samples, where criteria for selecting clasts for measurement was slightly different from those used in the field (Section 4.3.2).

The use of eigenvectors was proposed by Mark (1973) as an improvement on two dimensional methods of fabric analysis. This is discussed in Sections 4.2.7. and 4.6.1.

4.2.4. Small clast lithological analysis

Lithological analysis of gravel and till deposits is widely used by Quaternary scientists. A comprehensive description and detailed guidelines for conducting such analyses are provided in Bridgland (1986). It is a method that can conveniently be conducted alongside particle size analysis. Cheshire (1986) found that flint/quartz ratios of clasts in the +1.5 to -1.5 phi size range provided a valuable method of differentiating Anglian tills. This method has also been used successfully in the discrimination between tills by Allen (1984) and Allen *et al.* (1991).

4.2.5. Colour of till

Colour can be a secondary property which can vary considerably, depending not merely on the rock and mineral composition, but also on the degree of weathering. A fresh unweathered face of Lowestoft Till of dark blue/grey appearance, once exposed to the atmosphere will rapidly undergo oxidation and leaching, causing a colour change to brown or yellow (Madgett & Catt, 1978). For this reason, although colours are routinely recorded, care must be exercised when using this information to assist in the differentiation and correlation of till units. The Lowestoft Till has been shown to be remarkably uniform in character across southeast England (Perrin *et al.,* 1979), mostly present as a blue/grey chalky clay where it lies beneath the weathering zone.

In view of the above and the fact that recording the colour of each sample is relatively simple and quick, it was felt prudent to include this in the current work. It does not form the basis of subsequent correlation of till units, but it remains part

of the necessary comprehensive description of each sample and may well be required in future work.

4.2.6. Derived microfossils

Microfossils extracted from the till can be used as indicators of provenance in the same way as erratic lithologies. Knowledge of the micropalaeontology of bedrock likely to contribute to the content of the till is necessary, together with accurate identifications. Recent successful application of this method includes a study by Fish & Whiteman (2001), who used Chalk microfossils to indicate till stratigraphy across East Anglia.

4.2.7. Statistical analyses

Principal component analysis (PCA)/Principal co-ordinate analysis (PCO)

Principal component analysis is a powerful technique which evaluates the importance of each variable in a given set of data. This method was selected because data preparation was relatively quick and simple and the software (Multivariate Statistical Package by Kovach Computing Services) was readily available. PCA however, is not recommended where the variates exceed the number of samples (Kovach, 1995; Davis, 2002) and where this was the case, PCO was used. The latter is a more general form of PCA (Kovach, 1995), in which similarities are measured between samples rather than variables.

Use of the above methods of analysis in the current study enabled direct comparison with the data of Cheshire (1986) who used the same methods.

Eigenanalysis

Different modes of till formation are believed to produce different fabric properties, which can then be described by the use of eigenvectors/eigenvalues. This is the basis of studies of both modern and ancient tills where eigenanalysis has been used to infer modes of till origin (e.g. Benn, 1994; Dowdeswell & Sharp,1986; Hicock *et al.,* 1996).

Work on modern deposits of known origin has resulted in the publication of elongation and isotropy values for various types of till (e.g. Benn, 1995; Benn and Evans, 1996; Hart, 1998; Bennett *et al.,* 1999). Thus comparison of published

data with that collated in the current study could be carried out with relative ease. Although this method is the subject of some controversy (Bennett *et al.,* 1999), it was selected because it was believed it could provide an insight into the mode of till formation and involved little additional work. It also presented the chance to assess the value of such analysis of pre-Devensian tills.

4.2.8. Discussion of further methods

The following methods were also given consideration but rejected for the reasons given below.

Particle Shape

Particle shape (or form) is difficult to define, measure or categorise (Orford, 1990). Although there is much literature on the use of this method in the characterisation of till units, such analyses do not appear to have been used to any great extent for interpretative purposes. Samples collected for the current work did not contain sufficient clasts of large enough size for the use of shape sphericity indices based on axial ratios (Gale & Hoare, 1991). A visual assessment based on comparison with a chart such as that of Powers (1953) for sand sized particles is possible with the aid of a microscope. However, this is very time consuming and for tills found within the study area such a detailed investigation was considered to be unlikely to yield information of significant value.

Microfabric analysis

Some success has been reported by studying the alignment of till matrix particles (e.g. van der Meer, 1993; 1997; Khatwa & Tulaczyk , 2001). The method involves impregnating a block of undisturbed till with resin prior to cutting and grinding thin sections for subsequent detailed microscopic analysis. The method was rejected due to the lack of sites where such a block of till would be available, most of the samples in this study being obtained from drill cores or hand augered material. At only three sites (10, 25 & 30) would it have been possible to retrieve a suitable block of undisturbed till. Also the requirement for specialised equipment was prohibitive.

Heavy mineral analysis

It is possible that a change of direction of ice flow trajectory may be reflected in the heavy mineral content of the till. However, it is considered this would also be evident in the lithological analyses undertaken as part of this study. The latter method was favoured over the time-consuming heavy mineral analysis requiring specialized equipment and facilities not available during the course of this work.

Clay mineralogy

In general the clays present in the matrix of the Lowestoft Till are derived from a mixture of Lias, Oxford, Ampthill, Kimmeridge and Gault clays (Perrin *et al.,* 1979). In addition an insoluble clay grade residue from chalk and limestone debris may be present. The identification and correlation of tills which have not been subjected to extensive weathering may be possible (Madgett & Catt, 1978), but is considered likely to present a confusing picture, where different till units subjected to similar amounts of weathering may present similar clay mineralogies. It was also considered that major differences in the matrix fraction of the tills would be revealed by particle size analysis. The method also requires specialised equipment, so it did not form part of the current study.

4.2.9. Summary

Many of the analytical methods selected for this study were designed to replicate as closely as possible those used in earlier work by Cheshire (1986). This approach facilitates statistical comparison of data obtained in this study with that from Cheshire's tills at sites immediately to the south and southeast of the study area. Thus particle size, lithology, carbonate and where appropriate, macrofabric analyses were performed using methods developed by Cheshire (1986). Details of some of these procedures are provided in the appendices and referred to below. In other cases where modification was considered necessary, full details are given in the following sections.

4.3. Fieldwork

4.3.1. Sampling

A limited number of till outcrops exist within the study area, therefore samples were obtained wherever the opportunity arose to access a till unit at a depth of at

least 1 m which had not suffered obvious disturbance. As a result many of the samples were obtained from drainage ditches with a hand auger or from a dug trench where macrofabric measurements were taken. Three sites (10, 25 & 30), represented by two construction sites (Baldock and Caxton) and a quarry (Heath and Reach) presented the opportunity to take a vertical sequence of bulk samples at 1 m intervals. Sites 10 and 30 also provided a complete series of macrofabric measurements.

Accurate details of height and location were recorded and where appropriate site sketches and photographs were obtained. If the site was situated on sloping ground, the aspect and gradient were recorded. A minimum of 2.5 kg of material was collected for each bulk sample.

In all, 68 samples including 25 borehole samples and 43 bulk samples were obtained from 30 sites. The distribution of sites is shown in Figure 4.1 and details of sample locations, type and height are given in Table 4.1. Providing samples obtained from drainage ditches were uncontaminated and undisturbed, results from particle size and small clast lithology analyses were considered valid. The samples described in Chapter 5 are all considered satisfactory in this respect. Of the three locations where macrofabrics were measured in drainage ditches (Sites 16, 22 and 27), all samples were considered to be unmodified except sample 41 from Site 16 which lay on a southeast-facing slope ($<1.2^{o}$) making it possible that post-depositional slope processes have modified the original macrofabric. This is discussed in Section 6.6.2. The origin of these samples is borne in mind when discussing the results in Chapter 7.

4.3.2. Macrofabric analysis

Macrofabric analysis was performed in the field at Sites 10, 16, 22, 27 and 30 (Figure 4.1 and Table 4.1). Representative sections of till were selected at a depth of at least 1 m below ground level and measurements recorded as detailed below. Cheshire preferred a minimum depth of 1.5 m but the practicalities of constructing a trench of this depth at the sites mentioned above necessitated the selection of shallower material. Care was taken to avoid drainage channels and areas of post-depositional disturbance. Where sufficient measurements could

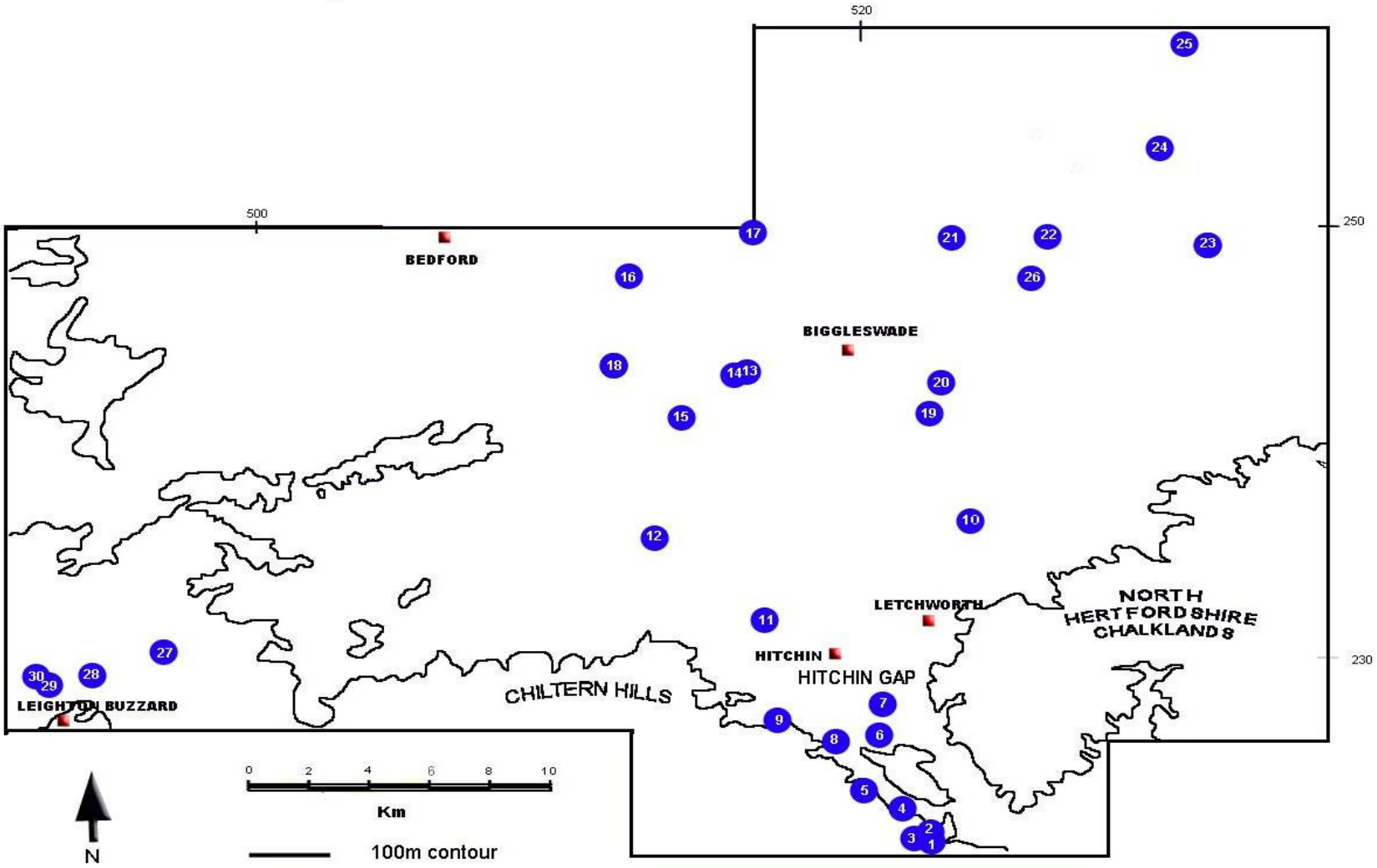

Figure 4.1. Site Locations.

Site No.	Location	O.S.Grid Reference	Sample number	Sample type	Height (m O.D)*
1	Knebworth Pk	TL2289 2150	1.	U100	102.3
			2.	U100	104.2
2	Norton Green	TL2288 2276	3.	U100	85.9
			4.	U100	98.8
3	Cannocks Wd	TL2240 2252	5.	Bulk	52.0
			6.	Bulk	64.1
			7.	Bulk	67.3
			8.	U100	70.4
			9.	U100	73.4
			10.	U100	76.6
			11.	U100	79.7
			12.	U100	81.5
			13.	U100	83.6
			14.	U100	85.6
			15.	U100	87.7
4	Letchmore	TL2167 2430	16.	Bulk	115.5
			17.	U100	116.0
			18.	Bulk	117.5
5	St Ibbs	TL1962 2662	19.	U100	68.8
6	Little Wymondley	TL2107 2753	20.	U100	66.5
			21.	U100	68.5
			22.	U100	70.5
7	Gt Wymondley	TL2176 2846	23.	U100	81.5
			24.	U100	83.5
			25.	U100	85.5
8	St Ippollitts	TL1960 2720	26.	Bulk	21.2
			27.	U100	39.0
9	Maydencroft	TL1800 2765	28.	Auger	78.5
10	Baldock	TL2346 3657	29.	Bulk -field	66.8
			30.	Bulk -field	68.1
			31.	Bulk -field	69.4
			32.	Bulk -field	70.7
11	Primrose Hill Quarry (Holwell)	TL1676 3200	33.	U100	27.0
			34.	U100	38.4
			35.	U100	41.0
			36.	U100	44.0

* Height at top of sample

Table 4.1. Sample Details (Contd. over/.)

Site No.	Location	O.S. Grid reference	Sample number	Sample type	Height (m O.D)*
12	Upper Stondon	TL1454 3569	37.	Auger	76.4
14	Broom	TL1605 4345	38.	Auger	38.5
15	Southill	TL1437 4130	39.	Auger	61.0
			40.	Auger	61.5
16	Moggerhanger	TL1320 4805	41.	Auger	53.4
17	Sandy	TL1653 5051	42.	Bulk -field	23.0
18	Warden Street	TL1120 4445	43.	Auger	78.0
			44.	Auger	78.5
19	Edworth	TL2217 4178	45.	Auger	43.5
20	Millowbury Farm	TL2277 4300	46.	Auger	53.5
			47.	Auger	53.0
21	Potton	TL2463 4950	48.	Auger	76.0
22	Cockayne H.	TL2555 4969	49.	Auger	73.5
23	Hatley	TL3058 4932	50.	Auger	76.5
24	Longstowe	TL2975 5380	51.	Auger	75.3
25	Caxton	TL3073 5806	52.	Bulk -field	51.4.
			53.	Bulk -field	51.9
			54.	Bulk -field	52.4
			55.	Bulk -field	52.9
			56.	Bulk -field	53.4
26	Wrestlingworth	TL2568 4838	57.	Bulk -field	49.4
27	Milton Bryan	SP9770 3045	58.	Auger	132.9
			59.	Auger	133.6
28	Potsgrove	SP9410 3069	60.	Auger	123.0
			61.	Auger	123.4
29	Munday's Hill	SP9362 2800	62.	Bulk -field	134.0
30	Heath & Reach	SP9314 2916	63.	Bulk -field	130.2
			64.	Bulk -field	132.2
			65.	Bulk -field	134.2
			66.	Bulk -field	136.2
			67.	Bulk -field	138.2
			68.	Bulk -field	140.2

* Height at top of sample

Table 4.1. Sample Details (Contd. from previous page).

not be taken in the field at Sites 27 and 30, oriented blocks of undisturbed till were removed to the laboratory for subsequent analysis.

During macrofabric analysis two measurements were made:

1) Down dip orientation from grid north
2) Angle of dip from horizontal

The first of these provides information regarding any preferred orientation of the clasts within the till, hence direction of ice movement, and the second is an indicator of the dynamism of the ice advance responsible for the deposition of the till (Rose, 1974).

Both measurements were taken from the a-axis of each clast using the procedure detailed in Appendix 1. Although this procedure was followed as closely as possible, at sites 16, 22 and 27 where till was exposed in drainage ditches, clasts had to be selected from a vertical section of till, the outer 4 cm first being removed. Measurement of clasts in the blocks of material removed from the site necessitated the use of criteria given in Section 4.4.2 below for borehole samples.

All clasts and till matrix were then discarded. Material for further analysis was obtained from an area adjacent to, and at the same depth, as that used in macrofabric analysis.

4.4. Laboratory Methods

4.4.1. Macrofabric analysis

Several borehole samples provided by the Three Valleys Water plc. and Biffa Waste Services Ltd. for this study were oriented during retrieval and the U100 tubes marked accordingly. Dr. D.A. Cheshire of the University of Hertfordshire kindly prepared details of this procedure and met the drillers to ensure orientations were accurately recorded.

The method of measuring clast orientation in these samples differed from that used in Section 4.3.2 and is described below. This method was also used for the oriented blocks described in the previous section.

Borehole Core Sample Preparation

Borehole samples were carefully extruded from the U100 tubes using a hydraulic jack. The orientation marked on the tube was scored into the clay during extrusion. The core sample was then divided into two equal lengths and the base trimmed to provide a horizontal surface. Each was then vertically mounted on a timber mounting board, supported by short non-magnetic nails. Using a compass, the orientation marked on the sample was aligned to the field orientation. Working across the surface of the core, dip and orientation values were recorded using the procedure given in Appendix 1. However, the criteria used to assess clast suitability varied slightly from those used when obtaining measurements from the field in that a) the specified minimum length of the a-axis was decreased to 10 mm due to the restricted number of clasts available in U100 samples and b) the width of the 'disturbance zone' to be avoided at the edge of the sample was reduced to 8 mm. Although a minimum of 50 clasts is usually considered a suitable size sample (Jones *et al.,*1999), in some cases insufficient material was available, therefore as many clasts as possible were recorded. Further discussion regarding these samples is found in Section 6.5.1.

In some cases the markings on the tube were ambiguous or unreadable. Measurements were obtained from these samples in the usual way and although no resultant vector could be calculated, analysis of the data provided a useful insight into the depositional environment.

All the material from the borehole core samples was retained for further analyses.

4.4.2. Preparation for further analyses

Each bulk sample was broken into small pieces (approximately 2 cm and smaller) to ensure a greater surface area to facilitate drying and the dispersion procedure that was to follow. This was then spread out on open trays to dry for at least 5 days at room temperature. The material was then sealed in a plastic bag and left for 48 hours to ensure a uniform distribution of the remaining moisture. The air-dried material was then divided at random without quartering or riffling, to provide the subsamples shown in Table 4.2. In selecting material for subsample c), clasts larger than 45 mm were avoided to ensure a statistically valid sample.

Similarly, an attempt was made to ensure a maximum clast size of approximately 5 mm in subsample d).

Procedures for particle size analysis above +4.0 phi (63 μm) were based closely on those adopted by Cheshire. Weights of subsamples a) to c) (Table 4.2) were slightly less than those used by Cheshire due to the limited amount of material available, particularly with borehole samples.

The weights of the first three subsamples were recorded and subsample a) was dried in an oven at 105 – 110^{o} C for 40 hours before being cooled in a desiccator. By driving off mechanical water in this way, subsequent re-weighing and comparison with the original air dried weight enabled calculation of the moisture content of the air-dried sample. Weights of the other two subsamples were then proportionally reduced to take into consideration their moisture content.

Sub-sample	**Weight**	**Purpose**
a)	~240 g	For determination of moisture content, after which this sample was unsuitable for further analysis.
b)	~900 g	For particle size determination in the range - 4.5 to +1.0ϕ (sieve analysis).
c)	~350 g	For particle size determination in the range +1.0 to +4.0ϕ (sieve analysis).
d)	~100 g	For particle size determination of finer fraction within matrix, i.e. particles less than 63μm (~ + 4.0ϕ) (laser diffraction method).
e)	~ 200 g	Microfossil analyses

Table 4.2. Subsample details.

4.4.3. Particle size analysis (> +4.0 phi and > +1.0 phi fractions).
Samples b) and c) (Table 4.2) were then dispersed in a solution of 8 g/l sodium hexametaphosphate without buffer. This process ensures deflocculation of the clay particles within the matrix binding the clasts together. The clasts are released and the fine clay particles can then be washed away through sieves. A separate nest of sieves was reserved for the final (dry) analysis. This removed the possibility of errors in the measured masses of each fraction resulting from

damage to the sieves during wet sieving/drying process. Any variation in the smallest mesh sizes in the different sieves used during wet and dry sieving may result in the loss of sample. Therefore, it was ensured that the smallest mesh size for each sample was less than that of the smallest particle size to be measured, i.e. the smallest mesh of sieve used for samples b) and c) being +1.5 phi and +4.5 phi respectively. Any organic material, such as rootlets, etc. was removed by flotation and repeated decantation before drying.

After overnight drying at 50^{o} C the samples were graded. This was achieved by passing the sample through a stack of British Standard sieves at half phi intervals. The stack was mechanically shaken for a minimum of 10 minutes in accordance with BS 1377-2 (1990), after which each sieve was carefully brushed out and the fraction weighed.

The distribution produced by this method may be subject to errors produced by carbonate cementing of multiple small grains, producing a single larger aggregate. One effect of this is discussed below.

4.4.4. Carbonate analysis

Following particle size analysis, the sieved fractions were placed together in an acid bath containing approximately 1 litre of 1 molar hydrochloric acid and left for at least 24 hours. The samples were stirred occasionally and the pH was tested when effervescence subsided. If required, further acid was added and the sample left for a further 24 hours. When effervescence had completely ceased, the samples were again checked for acidity before being removed from the bath. Stainless steel sieves were used to rinse away any remaining acid and after thorough rinsing in running water, samples were dried at 50 ^{o} C before being re-graded and weighed.

The above procedure efficiently removes all calcium carbonate clasts within the sample, but clasts of other lithologies may also be removed by this treatment. For most samples originating within and to the immediate north of the Hitchin Gap, the number of such lithologies was much less than the volume of chalk present. Of greater consequence, however, is the loss of limestone fragments in samples from the west of the study area, discussed further in Section 4.5.2. The

presence of high proportions of limestone in these samples was noted by a qualitative visual inspection of clasts in the size fraction between -4.0 and -2.0 phi. Typical examples are shown in Plate 4.1 where a comparison is made of sample 63 from Site 30 at Heath & Reach and sample 53 from Site 25 at Caxton (Plate 4.1).

Some insoluble clasts were cemented together with carbonates. The disaggregation of these following acid treatment caused the resulting smaller grains to be translocated down the sieve nest. Subsequent weighing of the phi classes would show an increase in the weight of the smaller class, i.e. giving a 'negative' weight for the acid-soluble content. This was noted in 17 samples and it was necessary to reduce the acid-soluble weight of these fractions to zero prior to statistical analysis.

If some of the acid-soluble content of a till has been removed by post-depositional decalcification, calculation of the original acid-soluble fraction of the till will not be possible. For this reason samples were obtained from depths below 1.0 m where weathering and therefore, decalcification, is less likely. An exception was sample 55 from Site 25 (Caxton) which was obtained at a depth of 75 cm. Care was also taken to avoid sampling tills that appeared to contain secondary carbonate.

4.4.5. Particle size analysis (< +4.0 phi fraction)

After undergoing training on the Malvern Mastersizer particle size analyser, time was spent devising suitable sample preparation techniques and conducting a pilot study. A report of this study is contained in Appendix 2. Although results were not completely as expected, it was concluded that they did provide a basis on which to discriminate between tills. The method used in the pilot was amended in that each sample was passed through a 63μm sieve before processing. This was due to difficulties experienced with the equipment when larger grains were included. Apart from this, the method was unchanged. Therefore, subsample d) was subjected to laser diffractometer analysis of the finer fraction within the matrix, recording the distribution of particles between 0.08 μm and 56.23 μm (~ +13.5 to + 4.2 phi), thus providing a small overlap with the subsample analysed by sieving.

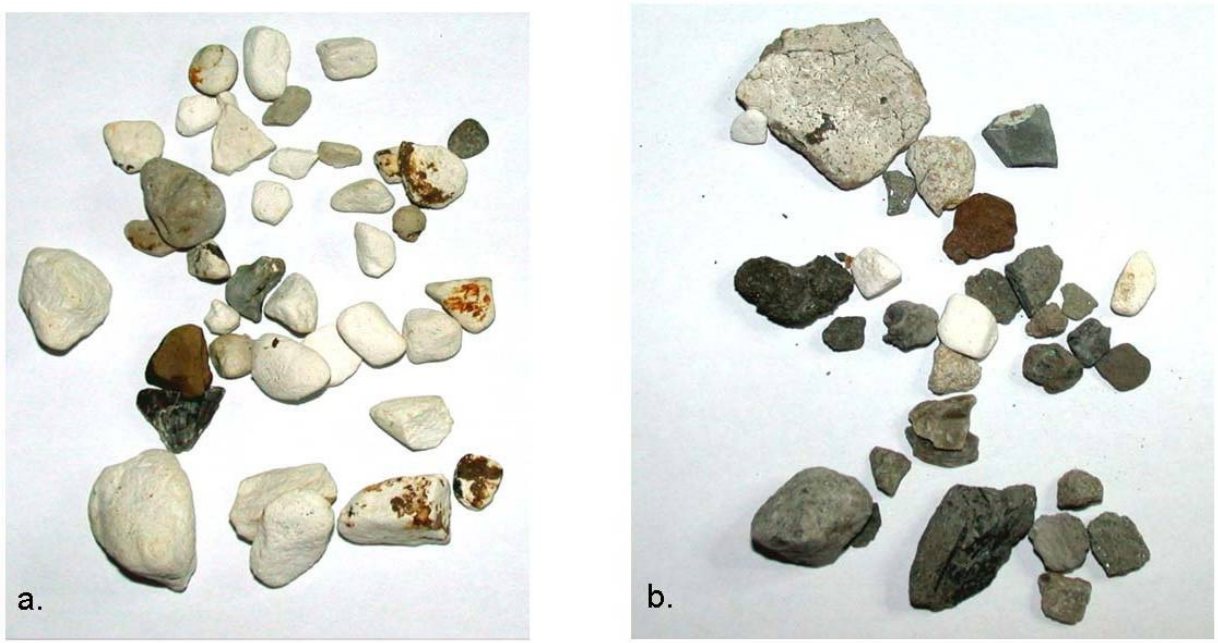

Plate 4.1

The acid-soluble clasts resting on -2.0 to -4.0 phi sieves of
a) Sample 53 from Site 25 (Caxton), and b) Sample 63 from Site 30 (Heath & Reach).
Clasts from Site 25 are mainly chalk, whilst those from Site 30 are mainly grey limestone.

The instrument used in these analyses was the long bench Mastersizer S. manufactured by Malvern Instruments Ltd.

It was not possible to assess particle size distributions of both the all-lithologies and acid-soluble lithologies distribution using this method. This is because the matrix has to be manually disaggregated through a sieve in order to remove clasts above 1 mm (see a) Sample preparation below). Fragile chalk clasts would be broken down into finer particles during this procedure, producing errors in the resulting distribution. For this reason the acid-soluble content was removed prior to analysis.

a) Sample preparation

Prior to weighing, the sediment was crushed lightly following the method of Perrin *et al.* (1979) and then carefully brushed through a 1 mm sieve. Approximately 100 g of sieved sediment was then immersed in 1 molar hydrochloric acid to remove acid-soluble content. Treatment consisted of repeated stirring of the sample over a number of days, until no further reaction occurred. The pH of the liquid was tested regularly by the addition of a fresh chalk clast to ensure a sufficient level of acidity remained. When all activity ceased (bubbles were no longer produced), rinsing was achieved by the addition of de-ionised water and particles above 63 μm were removed using a stainless steel sieve and discarded. After vigorous stirring, the material smaller than 63μm was allowed to settle for 24 hours before decanting the clear liquid above. To facilitate decantation some samples required the addition of a few drops of 1 molar magnesium chloride to aid flocculation of the clay particles. The procedure was repeated at least 3 times, until the acidity of the liquid was reduced. It was ensured that a pH value of between 7 and 8 was achieved prior to analysis. When as much of the liquid as possible had been poured away, the sample was left at room temperature for 3 days until sufficient liquid remained to allow thorough mixing but not to allow 'settling out'. Although this slurry was difficult to achieve it was felt that by using wet particles thorough mixing of the sample could be achieved, whereas if allowed to dry completely, size segregation of particles would occur. Also re-aggregation of clay particles might occur during the drying process.

b) Procedure

The subsample was added to the Mastersizer sample tank containing a solution of 4 g/l sodium hexametaphosphate to ensure dispersion. A single drop of surfactant (Nonidet P40) was added to prevent surface flotation. Very small quantities of material were needed to reach the level of obscuration necessary to achieve required level of scattering of the laser beam. Such small amounts were likely to reduce the chance of analyzing a representative amount of material. For this reason, each till sample was subjected to 10 separate analyses, fresh material being extracted from the subsample each time. Average values for the distribution were then calculated for each sample.

4.4.6. Small clast lithology

Cheshire (1986) successfully differentiated Anglian tills using small clast analyses in 7 half-phi classes. However, time constraints reduced the number of classes examined in this study to 5, i.e fractions resting upon the half-phi sieves of size -1.0 to +1.0 phi. A suitable subsample of clasts from each fraction was obtained by quartering. The average number of clasts examined in each sample (comprising the five sieved fractions) was 3,322, ranging from 2,055 to 5,669. This figure is well above the 500 clasts recommended by Bridgland (1986) to provide a detailed assessment of lithologies present. Using a low power (x 10, to x 20) binocular microscope, clasts were categorized into 13 types of lithology (Table 4.3). Explanatory notes provided by Cheshire assisted in this identification and are included in Appendix 3. The number of clasts in each category was counted and entered on data sheets found in Appendix 4 (CD in rear pocket). Unidentified clasts were also noted.

4.4.7. Colour of till

Air dried tills are significantly paler than their moist counterparts, often with a change in chroma and sometimes hue (Madgett & Catt, 1978). Therefore it was ensured that only the colours of moist samples were assessed in good daylight conditions (but not bright sunshine) using the Munsell notation. These are recorded in Chapter 5.

4.4.8. Microfossil analyses

A separate 200 g subsample of most tills (subsample e) in Table 4.2) was repeatedly washed and carefully dried. It was then sieved to remove the

fractions above +1.0 and below +2.5 phi. The remainder was examined with a microscope and the microfossils picked by hand and pasted onto microscope slides for identification by Dr. Adrian Rundle.

Most of the tills sampled in this study were analysed for microfossils although unfortunately some sites did not yield samples of suitable quality. The results are shown in Tables 7.23 and 7.24 and Figure 7.24. Unfortunately, the provenance of most of the microfossils could not be narrowed down to specific strata. Further, due to the geographic distribution of the geological outcrops ranging from northwest to northeast of the study area, these analyses did not yield information of any great value in assessing the direction of ice movement.

Category	Notes
Aggregates	Broad group of clasts including all aggregates of grains and/or minerals not included in the categories shown below (igneous, metamorphic & sedimentary)
Shale	Grey and mottled brown types.
Flint	Includes nodular, rounded, patinated varieties.
Quartz	Includes rounded to angular, usually transparent to translucent.
Acicular	Quartz of needle-like habit.
Fe Nodules	Includes limonite and goethite and partially altered clasts.
Fe Aggregates	Aggregates of the above.
Pyrites	Usually in the form of pyritised fossils.
Fossil	Decalcified and siliceous fossil remains.
Coal	Shiny black or brown.
Rhaxella chert	Distinctive variety of chert with moulds of *Rhaxella perforata sponge.*
Decalcified limestone	Clasts of silica-replaced limestone, containing fossils or ooliths.
Whorl	Chalcedonic clasts of distinctive whorl shape.

Table 4.3. Categories of lithology used in small clast lithological analyses.

4.5. Discussion on procedures

4.5.1. Deflocculation

The use of 2 g/l of sodium hexametaphosphate as specified in BS1377 (1990) was found to be ineffective in dispersing the clay matrix. Therefore following Cheshire's work a solution of 8 g/l was used.

Cheshire processed samples in 2-litre containers using an end-over-end shaker to facilitate dispersal of the clay material. However, problems were noted in that samples required a longer period of treatment (4.5 hours) than that recommended by BS1377 (1975), with further mechanical disaggregation sometimes required (Cheshire, 1986). It was considered that this may lead to abrasion and fragmentation of particles during such prolonged shaking. Therefore a trial was carried out in which samples dispersed by the above method were compared with those simply left to soak for several days in a bucket containing 8 g/l sodium hexametaphosphate solution, being stirred thoroughly (but not necessary vigorously) two or three times per day. A greater quantity of dispersant was used - 3 litres for subsample (ii) and 4 to 5 litres for subsample (iii). It was considered that extra time was needed for the dispersant to penetrate the clay and that the additional liquid/space facilitates better mixing. This procedure proved to be more effective, requiring a shorter rinse time. A few samples required additional treatment and it was found that the addition of warm dispersant proved effective in these cases. Results of this trial are shown in the particle distribution graphs in Figure 4.2. In the -2.0 to +4.5 phi range all but one sample (Sample 9), show consistently higher percentages in the distributions produced by the revised method. Comparison of particles larger than -2.0 phi is impossible due to the small number of clasts present in these fractions. However, it is noted that even here, samples produced by the shaking method produced lower values.

A further advantage is that complete deflocculation can be confirmed by examining the sediment at the bottom of the bucket before rinsing is attempted. If sediment remains after stirring, then further treatment is required.

Although the differences shown above were small, where tills contain higher proportions of chalk these differences may become more important. Here,

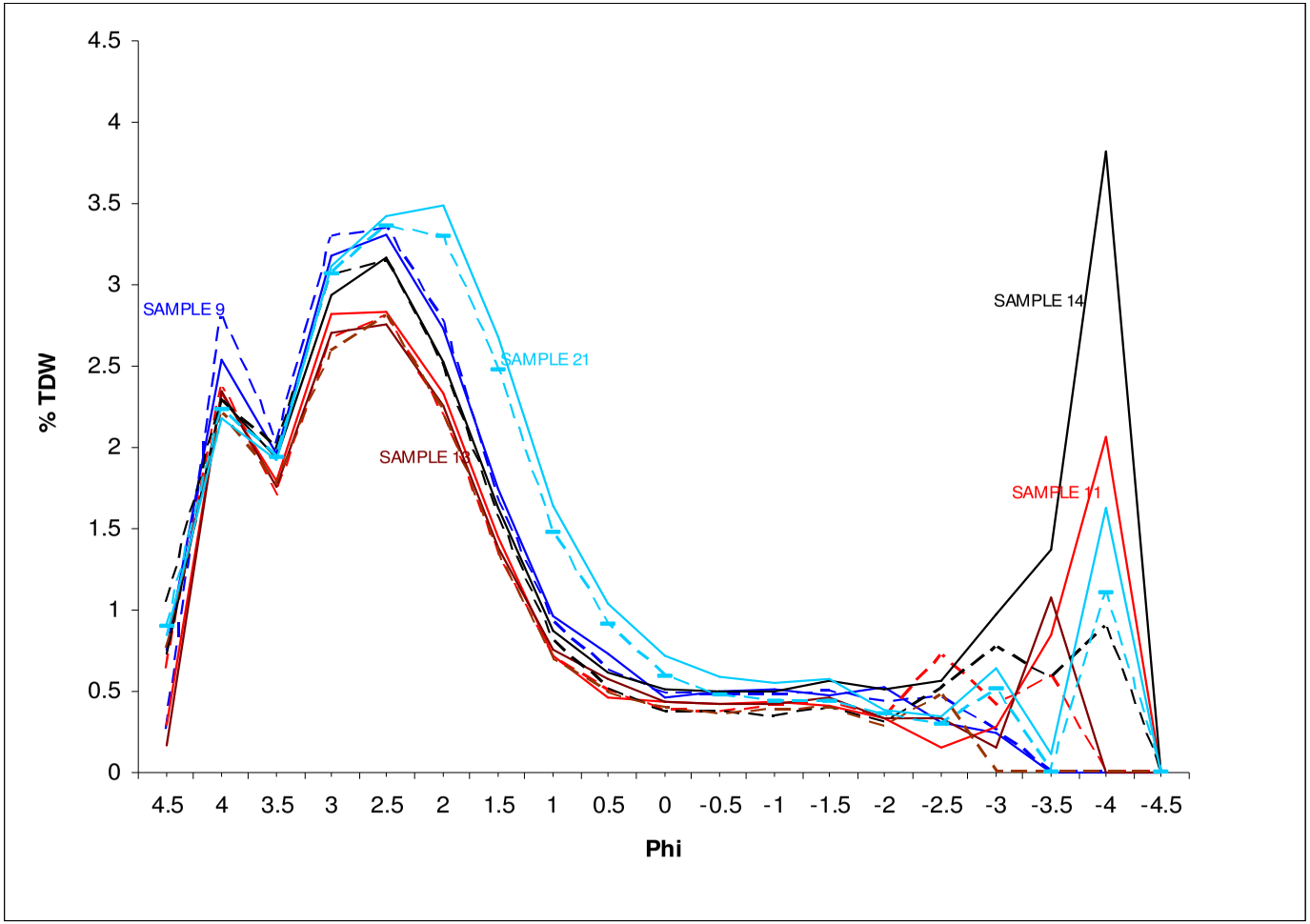

Figure 4.2. Deflocculation trial for samples 9, 11, 13, 14 & 21.

Particle size distributions produced using a) deflocculation by end-over-end shaking (broken lines) and b) dispersion by soaking and stirring (solid lines). Graph shows percent of total dry weight (%TDW) against half-phi size.

fragmentation of chalk particles produced by prolonged mechanical agitation may result in increasing amounts of debris being redistributed into finer, e.g. +4.0 and +4.5 phi classes. It was considered likely that some tills within the current study area, in particular those lying close to the chalk escarpment, were likely to possess higher chalk content than those of the Lea basin. For this reason, the use of an end over end shaker was not employed during this study. Although this amendment to the procedure used by Cheshire may to a small degree affect statistical comparison of data, this factor is likely to be outweighed by differences produced where high carbonate contents were present.

4.5.2. Carbonate analysis

The method involving the use of 1 molar hydrochloric acid to dissolve calcium carbonate was necessary to ensure compatibility with Cheshire's data. However, it was realised that tills lying in the west of the current study area differ from those present in the Lea Basin in that the latter contain very few limestones other than Chalk. In particular, many of the samples obtained from Sites 29 and 30 at Heath and Reach contained relatively numerous limestone and fossil fragments especially notable in the size fractions greater than -1.0 phi. Therefore, the above method does not give an accurate indication of the amount of chalk present. For this reason, figures produced for chalk content in the west of the study area, at Sites 27 to 30 would be considered unreliable. The ideal solution to this problem would be to remove the chalk clasts without destroying the limestone, prior to clast lithological analysis. At present no suitable method has been devised to facilitate this.

4.6. Statistical analyses

In order to characterize the tills, the data were processed to provide graphs of particle size and carbonate distributions and lithological content. These provided the means of differentiating tills from the west of the study area from those in the northeast.

4.6.1. Macrofabric

Fabric measurements, i.e. downdip orientations and dip values, were analysed using the Oriana program developed by Kovach Computing Services. The

resultant vector, vector magnitude, average dip and statistical significance were recorded.

Macrofabrics at 8 sites appeared to reflect the expected direction of ice movement, although 6 of these could have been modified by flow processes, whilst at Sites 6 (Little Wymondley) and 30 (Heath and Reach) possible transverse fabrics were recorded.

The use of StereoNett, a shareware program developed by Johannes Duyster of the Institut für Geologie, Ruhr-Universitat-Bochum, Bochum, Germany, provided eigenvalues and eigenvectors. The latter yield information regarding the character of the till fabric as described by Dowdeswell & Sharp (1986). Three mutually orthogonal eigenvectors are produced, the first (principal) eigenvector representing the axis of maximum clustering in the data, the degree of clustering being represented by $S_{1,}$ - the normalized vector magnitude (eigenvalue). S_2 and S_3 are the respective eigenvalues for the second and third eigenvectors (Andrews, 1971; Mark, 1974).

A plot of S_3/S_1 (May diagram - Dowdeswell & Sharp, 1986) was constructed to provide visual representation of fabric strength (Figure 6.1). Data were also plotted on an equilateral ternary diagram scaled by fabric isotropy ($I=S_3/S_1$) and fabric elongation ($E = 1-(S_2/S_1)$ as described by Benn (1994) (Figure 6.2).

Fields delineating different modes of till genesis are shown in Figure 6.3, generated from data obtained from modern glacial environments (Dowdeswell & Sharp, 1986).

Few workers have applied this method to Anglian tills, exceptions being Fish (2000) and Etienne (2001). The former applied eigenanalysis to tills across East Anglia and samples from Primrose Hill Quarry (Site 11, this study) were studied by Etienne. In both cases, the tills were identified as deformation tills.

Despite the fact that most of the Lowestoft Till within and adjacent to the study area has previously been believed to represent a typical lodgement till, data from this study revealed only two examples, at Sites 1 (Knebworth Park) and 5 (St

Ibbs), of undeformed lodgement till. Some of the remaining samples are associated with flow/slumped till, but many samples are suggested to have undergone at least minor deformation. This is taken to reflect deformation processes described by Hart (1995) where till is deposited above deformable bedrock.

Further discussion regarding different types of till and their associated eigenvalues is found in Section 6.5.

4.6.2. Particle Size Data

Output from particle size analysis, both sieve and laser diffraction, were recorded on Excel spreadsheets. Data derived from these two methods are based on different physical properties of the particles and cannot therefore be considered to form part of the same distribution (Matthews, 1991). Thus, separate distributions were recorded for data supplied by each method.

Analysis of particle size data led to identification of tills at Sites 2 (Norton Green), 7 (Great Wymondley), 16 (Moggerhanger) and the Middle Till at Site 11 (Primrose Hill Quarry), with low quantities of fine material. This, together with their macrofabric properties (Chapter 6) suggests them to be flow or slumped tills. Local input from the Lower Greensand at Sites 15 (Southill) and 18 (Warden Street), was suggested by very high modes in the medium to fine sand fraction and low acid-soluble contents.

4.6.3. Multivariate analysis

The data collected were subjected to statistical analysis in order to determine the presence or otherwise of till groups which may then be assigned to different stratigraphic units.

Data from particle size analyses, acid solubility and small clast lithology provided a total of 88 variates. These were reduced to 85 by selecting those showing the greatest variance. Thus the main dataset (Dataset 1) comprises 85 variates for 67 samples. For an additional sample (5) 71 variates only were available.

Principal component analysis involves an eigenanalysis performed on a correlation or covariance matrix. The results are expressed in the form of principal component axes dissecting the array of datapoints in multidimensional space. The eigenvectors are composed of the component loadings for each axis, which indicate the measure of relative importance of each variable within the axis. The sign of the loading indicates which end of the axis the variable is associated with (Kovach, 1995). The eigenvalues (component loadings) show the total variance accounted for by each axis, the first axis being the largest. The first three or four principal component axes are extracted, although the fourth axis usually represents only a very minor percentage of the variance.

The loadings on each of the first three axes have been expressed in graphical form by multiplying each element of the eigenvector by the square root of its associated eigenvalue (Davis, 2002). Thus a comparison of the importance of the variables on each axis can be made.

The similarity matrix is used to identify those pairs of samples with the highest similarity coefficient. By constructing links between samples with progressively lower similarity coefficients the presence or otherwise of discrete groups of samples can be revealed. The lowest similarity coefficient used to construct these links varies with each dataset. These links are shown on the scatter graphs of the principal component case scores for the first two axes.

PCA, however, is not recommended where the variates exceed the number of samples (Kovach, 1995; Davis, 2002). According to Grimm & Yarnold (1995) the most satisfactory results are obtained when sample to variate ratio is greater than or equal to 5. Although this ratio was only achieved in Dataset E, principal component analysis was carried out on all datasets where sample numbers exceed variate numbers. To facilitate this, the main database (Database 1) was divided into 7 subsets, details of which are given in Table 4.4. In subsets A, D, F and G, where variate numbers remain high, principal co-ordinate analysis (PCO) was carried out. This is a more general form of principal component analysis (Kovach, 1995), in which similarities are measured between samples rather than variables.

DATABASE 1.

Main database - 85 variates.

14 particle size data in half φ classes from -2.5 to + 4.0φ (sieve analysis)
14 acid soluble data in half φ classes from -2.5 to +4.0φ (sieve analysis)
44 particle size data classes between 0.08 and 56.2 µm (laser diffraction)
13 small clast lithology classes

67 samples - 85 variables
1 sample - 71 variables (acid soluble data missing)

SUBSETS:

Dataset A - all samples and variates (as above)

Dataset B - 14 variates, 68 samples
Particle size data in half φ classes from -2.5 to + 4.0φ (sieve analysis)

Dataset C - 14 variates, 67 samples
Acid soluble data in half φ classes from -2.5 to +4.0φ (sieve analysis)

Dataset D - 44 variates, 68 samples
Particle size data classes between 0.08 and 56.2 µm (fine matrix)

Dataset E - 13 variates, 68 samples
Small clast lithology in half φ classes from -1.0 to + 1.0 φ.

Dataset F - 85 variates (as for dataset A) 41 samples
Data from sites excluding 1 – 8 within the Hitchin Gap.

Dataset G – 85 variates (as for dataset A) 35 samples
71 variates for 1 sample (acid soluble data missing)
Data from sites in and adjacent to Hitchin Gap only.

DATABASE 2

Includes all data from Database 1 and a further 77 samples from other areas for comparison

39 variates:
14 particle size data in half φ classes from -2.5 to + 4.0φ (sieve analysis)
14 acid soluble data in half φ classes from -2.5 to + 4.0φ (sieve analysis)
11 small clast lithology classes

144 samples – 39 variates
1 sample – 25 variates (acid soluble data missing).

Table 4.4. Summary of datasets used in multivariate analyses.

Neither PCA nor PCO can be performed where data are missing. Data concerning the 'all-lithologies' fraction were not available for Sample 5, which had therefore to be omitted from these analyses. It was, however, possible to perform cluster analyses on the full 68 samples. Cluster analyses are also used to divide a set of samples into discrete groups according to their characteristics. There is a wide variety of methods of achieving this and that most useful to the current study was an agglomerative weighted pair group method using averages (WPGMA). This gives equal weight to all clusters irrespective of how many samples are present in each cluster (Kovach, 1995).

Cluster analysis was also performed on all datasets and results are shown where this provides additional or supporting information.

On its own, multivariate analyses did not provide a suitable basis on which to differentiate tills within this study, but it allowed the comparison of a variety of characteristics. As a result, more detailed analyses were performed, leading to the separation of samples in the east and north from those in the west of the study area. Specifically, separation of tills was achieved on the basis of the quantity of fine material (<+4.5 phi) present and the flint/quartz ratio.

4.6.4. Comparison with previous data

Database 2 comprises all the data collected during this study together with a selection of data kindly supplied by Dr. Allan Cheshire, details of which are given in Table 4.5. The purpose of analysis of this comparison dataset was to assess the possibility of extending Cheshire's regional stratigraphy across the present study area, by correlation of till units. Similarity links were generated between Cheshire's comparison sites and those investigated as part of this study. Links between sites up to 20 km apart are considered in Section 7.5. It is considered unlikely that high similarities between samples lying at greater distances represent a laterally continuous unit (Cheshire 1986).

It was possible on the basis of analysis of this database to correlate tills within the Hitchin Gap with those to the southeast of the study area, identified by Cheshire as part of the Ware Member Till.

Sample Code	Grid Ref	Location	Sample Code	Grid Ref	Location
BARK 1	TL381366	Barkway pit	**HH 2**	TL263116	Holwell Hyde
BARK 2	TL381366	Barkway pit	**HH 4**	TL263116	Holwell Hyde
BBA	TL314102	Bayfordbury	**HH 6**	TL263116	Holwell Hyde
BIGR 1	TL290119	Birch Green	**HH 8**	TL263116	Holwell Hyde
BPH2	TL336117	Ball Park Hertford	**HH 10**	TL263116	Holwell Hyde
BUNTU 2	TL355298	Buntingford	**LG**	TL360222	Levens Green
BUNTU 4	TL355298	Buntingford	**LWF**	TL204343	Lower Wilbury Farm
BWA	TL341105	Balls Wood	**PHQU 1**	TL157320	PH Quarry
CCL 1	TL362168	Cold Christmas	**PHQU 2**	TL157320	PH Quarry
CCU1	TL362168	Cold Christmas	**PHQU 3**	TL157320	PH Quarry
CCU2	TL362168	Cold Christmas	**PHQU 4**	TL157320	PH Quarry
COT 1	TL325295	Cottered	**PHQUS**	TL157320	PH Quarry
COT 2	TL325295	Cottered	**PLPL**	TL353167	Poles Lane Pit
COT 3	TL325295	Cottered	**SPW**	TL226139	Sherrardspark Wd
COT 4	TL325295	Cottered	**TURA 1**	TL232122	Turmore Dale
COT 5	TL325295	Cottered	**WAT 1**	TL299200	Watton By Pass
COT 6	TL325295	Cottered	**WAT 3**	TL299200	Watton By Pass
COT 7	TL325295	Cottered	**WES**	TL256304	Weston
DLL 1	TL377213	Dowsetts Lane	**WHP**	TL290211	Whitehall Pit
DLL 2	TL377213	Dowsetts Lane	**WMUEB**	TL344158	Westmill Quarry
EGJR 7	TL296106	Eastend Green	**WMUNX**	TL344158	Westmill Quarry
EGJR 8	TL296106	Eastend Green	**WMUSX**	TL344158	Westmill Quarry
EGL 1	TL296106	Eastend Green	**WMU 1**	TL344158	Westmill Quarry
EGUA	TL296106	Eastend Green	**WMU 2**	TL344158	Westmill Quarry
FGB	TL223258	Fisher Green	**WMU 3**	TL344158	Westmill Quarry
FOXEC	TL341123	Foxholes	**WMU 4**	TL344158	Westmill Quarry
FOXS 1	TL341123	Foxholes	**WMU 5**	TL344158	Westmill Quarry
FOXS 3	TL341123	Foxholes	**WMU 6**	TL344158	Westmill Quarry
FROL 1	TL285206	Frogmore Watton	**WMU 7**	TL344158	Westmill Quarry
FROL 2	TL285206	Frogmore Watton	**WMMEM**	TL344158	Westmill Quarry
HC 1	TL277104	Holwell Court	**WMMA**	TL344158	Westmill Quarry
HC 8	TL277104	Holwell Court	**WMMF**	TL344158	Westmill Quarry
HC 16	TL277104	Holwell Court	**WMW 1**	TL344158	Westmill Quarry
HHF 1	TL339332	Hyde Hall Farm	**WMW 2**	TL344158	Westmill Quarry
HHF 3	TL339332	Hyde Hall Farm	**WMW 3**	TL344158	Westmill Quarry
HHF 7	TL339332	Hyde Hall Farm	**WMW 4**	TL344158	Westmill Quarry
HHF 8	TL339332	Hyde Hall Farm	**WMW 5**	TL344175	Westmill Quarry
HHL	TL263116	Holwell Hyde	**WRS 1**	TL295192	Watton Railway StN

Table 4.5. Details of locations of comparison data used in analysis of Dataset 2.