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SEDIMENTARY ENVIRONMENTS OF THE

BOVEY BASIN

A thesis submitted to
The University of Surrey, for the
Degree of Master of Philosophy
in The Department of Civil Engineering

By

Anthony Vincent, B.Sc.

OCTOBER 1974.
ABSTRACT

The Bovey Basin is one of three sources of 'ball clay' in the South-West of England, 'ball clay' being a secondary kaolinite, the name of which is derived from the original method of working.

Various techniques for the investigation of very fine grained materials are reviewed and described, and the sedimentary structures in sands, silts, and clays are reviewed, with emphasis on structures formed in the early consolidation stages of fine grained sediments.

The literature of the Bovey Basin is reviewed and the stratigraphy and structure are described. The Basin has had a complex sedimentary history and ten Stratigraphic Members can be recognised, with a large unconformity between the earlier group of six members and the later group of four members. The Basin was probably being filled throughout the Lower Tertiary.

The ball clays are shown to have settled in a flocculated condition from high concentration slurries in a lacustrine environment which, although shallow, did not dry out. Fine grained carbon and fine quartz strongly influenced flocculation, together with the pH of the environment. The kaolinite had three possible provenances:

(a) a very fine disordered kaolinite derived from country rock.

(b) a coarser grained well ordered kaolinite derived from hydrothermal kaolins on Dartmoor.

(c) a medium grained medium disordered kaolinite derived either from the weathering of felspar in the Dartmoor Granite or from mixtures of (a) and (b).
The sands are shown to have been sedimented in outwash fans and to have been derived from the Dartmoor Granite.

Lignites accumulated in backswamps, the vegetation being swept into the sedimentary area.

The complex stratigraphy of the Bovey Basin resulted from the moving around of these sedimentary environments, controlled by tectonic sagging in association with the Sticklepath Fault System, coupled with the changes in provenances as the Dartmoor Granite became further unroofed. The two commercially important members, the Abbrook Member (fine disordered kaolinite) and the Southacre Member (well ordered white firing kaolinite) are the oldest of the known sequence and are well exposed around the eastern outcrop, the western outcrop being buried under the unconformable later group of members.

The Geotechnical Properties of the ball clays are shown to depend largely upon the lithology of the sediment.
ACKNOWLEDGEMENTS

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The author would like to express his appreciation to Dr. N. E. Simons (Reader in Geotechnical Engineering, Department of Civil Engineering, University of Surrey), and to Mr. D. Mitchell (Technical Director, Watts, Blake, Bearne & Co. Ltd.) who supervised this research, and to thank them for their continued interest and advice.

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1. INTRODUCTION

1.1. There are two areas of supposed Oligocene strata in Devon, and an area of Eocene age in Dorset, which for the past two and a half centuries have been worked for "ball clay". The derivation of the name "ball clay" is obscure but it is probably derived from the manner in which it was worked until comparatively recent times. "The term 'ball clay' does not refer to any particular property of the clay, but is derived from the original method whereby the clay was obtained by cutting it on the floor of open pits into cubes, or balls, the size being about 10 inches across and the weight 30 to 35 lbs". (Scott, 1929). Plate 1.1. is a photograph taken in the 1930's at North Devon, which illustrates the method of working and the specialised tools used, as well as the "balls" ready for loading out of the pit.

PLATE 1.1.
The term "ball clay" was coined in the early days of pipe making (W.B.B.), and has since passed into general use to describe the highly plastic, white burning, secondary clays which are an essential constituent of most pottery bodies.

1.2. The three ball clay areas in South-West England are virtually unique, although other areas are worked for "ball clays" (e.g. the Westerwald in Germany), but the clays are generally inferior in ceramic quality. The three areas are shown on FIG.1.1. which illustrates the general geology of Devonshire and Dorset. The dominant clay mineral in each area is kaolinite.

The supposed oldest of the three areas is in Dorset, where the clays have been extensively worked around Poole and Wareham. The ball clays are found intercalated with sands of Bagshot age and are characterised by extremely fine grain size (e.g. 95% less than 5 microns - W.B.B.), with high plasticity, high strength and a long firing range. Although the Dorset ball clay area is some 105 km (65 miles) from the nearest point of the Dartmoor Granite, Cosgrove and Salter (1966) and Gilkes (1968) imply that the source of the kaolinite in the Dorset ball clays was in fact the granite masses. Gilkes also shows that further to the east the dominant clay minerals of the Bagshot of the Hampshire Basin become montmorillonite-illite mixtures rather than kaolinite-illite mixtures found to the west, which Gilkes considers indicates a different provenance.

The Bagshot Beds of Dorset have the largest outcrop area of the three deposits. They also have the shallowest depth being in the order of 76 metres (250 feet) deep near Wareham (W.B.B.). Overlaps and offlaps cause the ball clay seams to be rather lenticular in nature, and to be best developed to the south of Wareham and around Poole.
1.3. The two ball clay areas of Devonshire are associated with the Sticklepath Fault system which cuts across the country from near to Bideford in the north-west to Torquay in the south-east. The deposits of the Petrockstow Basin consist of Lower Tertiary unconsolidated clays of varying silt content, silts, sands, gravels and lignites deposited in a partly fault-controlled sediment basin which is thought to be a relic of a river system. This river probably flowed from a south-easterly direction, mainly following the line of the Sticklepath Fault zone and entering the sea in the Bristol Channel area (Freshney and Fenning 1967). Sedimentation appears to have been controlled by contemporaneous fault movements, mostly along north-west to south-east lines. This faulting divides the basin axially into a deep central trough with flanking shelf areas. The trough sedimentation is characterised by silts, sands, gravels and extremely silty clays. In the marginal shelf areas, gravels and coarse sands are almost absent and clays, often brown with a variable silt content, are dominant (Freshney 1970 and W.B.B.). During examination of the cores from three Institute of Geological Sciences' boreholes, Freshney concluded that deposition was cyclical.

The North Devon or Petrockstow ball clays obviously have genetic affinities with the South Devon or Bovey ball clays but the type of clay present bears a greater resemblance to the Dorset clays than to the South Devon clays. The North Devon clays are fine grained (e.g. 89% less than 5 microns - W.B.B.), and are generally plastic. Disordered kaolinite is the dominant mineral with a small amount of illite as a secondary component, with occasional traces of montmorillonite (W.B.B.). The combination of this mineralogy and fine particle size yields a clay exhibiting exceptional plasticity over a wide range of moisture contents, high green strength and wide firing range. This clay is therefore ideally suited to complement other clays of widely varying properties. The Petrockstow Basin is the smallest in area of the three ball clay areas but is 671 metres (2200 feet) deep. (Freshney 1970).
1.4. The South Devon ball clays occur in the neighbourhood of Bovey Tracey and Newton Abbot. This area is known as the Bovey Basin and is certainly the deepest of the three ball clay deposits. The depth of this basin is certainly in excess of 900 metres (3000 feet) and on gravity survey Fasham (1971) estimates the depth to be 1300 metres (4200 feet). The depth on gravity measurement depends on the density of the material present and, as the lower two-thirds of the strata is overstepped by the later Bovey deposits and the deepest borehole to date (March 1974) only reached 320 metres (1054 feet), the density of the larger part of the Bovey strata is not known. In the deep boreholes, considerable thicknesses of lignite were encountered which appear to be thickening towards the centre of the basin. If this trend continues, then the average density would be reduced which could well reduce Fasham's estimate of the depth of the basin.

The strata of the Bovey Basin consists of clays, sandy clays, sands, siliceous clays, carbonaceous clays, lignitic clays and lignite. (The differentiation between sandy and siliceous and carbonaceous and lignitic is one of particle size of the non-clay material). The lignites are different from the North Devon lignites in that no seat earth has been identified and they reach considerable thicknesses. The Bovey Tracey lignites suggest an accumulation of plant debris, with a rich abundance of Sequoia, Osmunda and Calamus, which was swept into the Bovey Basin under warm tropical rainforest conditions. These plant remains are the only fossils so far found in the strata. Chandler (1957) suggests that many Tertiary species have a long range in time and cannot therefore be useful in determining age. However, the slow replacement of some species and genera by others with the passing of successive Tertiary stages affords evidence suggesting a Middle Oligocene age for Bovey Beds and hence, by inference, it is suggested that the North Devon Basin is of the same age.
The sands of the Bovey Basin are sub-hedral quartz grains with occasional tourmaline, usually in a fine-grained silica flour bound with some kaolinite. The sands appear to be of granitic origin.

The clays are fine grained although, for equivalent silica content, not as fine as either the North Devon or the Dorset ball clays (e.g. 85% less than 5 microns - W.B.B.). The clays are dominantly medium to well ordered kaolinites with very small amounts of illite. This implies the dominating influence of the Dartmoor Granite where, some 32 km (20 miles) to the south-west of the Bovey Basin, the coarser, well crystallised kaolinites of hydrothermal origin are worked for china clay. The slightly coarser particle size distribution of the ball clays in conjunction with the lack of other clay minerals reduces both the ceramic strength and plasticity of the South Devon ball clays in comparison with the North Devon and Dorset ball clays but the carbonaceous and other low silica clays fire white (the "whiteware" clays of Scott 1929), a property which makes the Bovey ball clays of paramount importance. The Bovey Basin sustains the largest output of the three areas and is currently producing some 500,000 tonnes of ball clay annually, of which some 70% is exported through the Port of Teignmouth mainly to European markets.

1.5. The Bovey Tracey Basin can be divided into two geographical areas. The northern and longer of the two areas is a rough parallelogram stretching in a north-westerly direction from Newton Abbot to beyond Bovey Tracey, a distance of some 11 km (7 miles). The greatest width is from Blackpool in the south-west to Gappah in the north-east, a distance of some 8 km (5 miles). Hence, the Basin covers an area of some 44 square kilometres (17.2 square miles). The southern area, to the south of Newton Abbot, stretches from Decoy to Aller, and is described by Scott (1929) as a "nearly circular area two miles in diameter" but also includes large areas of Aller Gravel, Greensand and a faulted inlier of New Red Sandstone, as well as the Bovey material.
The greater part of the area is low-lying, not attaining 61 metres (200 feet) except in the extreme north-west of the basin around Lower Brimley. The western third of the basin is generally over 30.5 metres (100 feet) in height, whilst most of the remainder is occupied by the broad gentle valleys of the River Bovey and the River Teign, which reach a confluence at Twyne ("yeo" is a West Country name for a river) in the centre of the basin. The ground surface only rises above 30.5 metres (100 feet) again at Chudleigh Knighton, in the area between the two rivers. Most of the river valleys within the basin are below 15 metres (50 feet) in level and the River Teign leaves the basin at an elevation of less than 1 metre above sea level, giving rise to a low-lying marshy area to the north of Newton Abbot (East and West Golds and Zitherxton).

The boundaries of the basin are largely with Culm and Devonian Slates, with some intrusives of Devonian age to the south-west, Devonian Limestone at Kingsteignton and, generally, New Red Sandstone to the south of Newton Abbot. The western boundary is parallel to the Sticklepath Fault trend and is characterised by a fault scarp rising to over 138 metres (450 feet) at Rora Wood, Penn Wood and to the west of Colesworthy. The south-western margin also appears to be fault controlled with the sharp features of Ingsdon Hill (186 metres - 612 feet), Greenhill (82 metres - 270 feet), Darracombe Beacon (95 metres - 313 feet), Gaze Hill (99 metres - 326 feet) and Knowles Hill (64 metres - 211 feet) reflecting the outcrops of Devonian intrusives.

The slopes on the other two sides are more gentle, rising on the east towards Haldon and on the north-east towards the Teign Valley and the eastern extremities of the Dartmoor Granite.
1.6. For commercial reasons, inferred information attributable to Watts, Blake, Bearne & Company Limited's sources cannot be confirmed by inspection of records, reports or technical information by any person outside the W.B.B. organisation. Where this information source is used, it is attributed as W.B.B.

The Bovey Basin has been commercially exploited for some two hundred and fifty years but it is only in the past two decades that mergers between the once numerous producing companies and advances in drilling techniques (Vincent 1971) have allowed an integrated overall picture of the structure and stratigraphy of the Bovey Basin to emerge. It is the sedimentology of the Bovey Basin based upon this overall picture which is the concern of this thesis.
2. LITERATURE REVIEW OF SEDIMENTARY TECHNIQUES IN CLAYS.

2.1. The fine-grained plastic sediments can generally be divided into two grades, namely silts and clays. The separating dimension is usually placed at 4 microns, although in Hall (1912) the definition of clay is given as "predominate parts smaller than 2 microns", and Cartwright (1928) places the limiting dimension as 5 microns. It is interesting to note that these definitions place 'china clay' in the silt grade simply on the particle size distribution.

A more general definition, which would accord with all uses of the word 'clay', would be "a fine-grained material composed predominantly of clay mineral". Whichever definition is used, the ball clays more certainly come under the heading of 'clays', being 80% less than 2 microns (equivalent spherical diameter) and composed mainly of kaolinite.

- 96% less than 20μ e.s.d.
- 92% less than 10μ e.s.d.
- 88% less than 5μ e.s.d.
- 80% less than 2μ e.s.d.
- 72% less than 1μ e.s.d.
- 53% less than 0.5μ e.s.d.

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2.2. Particle size analysis of clays is very seldom mentioned in sedimentological literature, most writers simply stating that the sediment is fine skewed when clay material is present. This is hardly surprising as the particles are very small and cannot be graded on sieve analysis (the finest practical mesh being 53 microns).
An added complication is the general platy nature of the particles, requiring the introduction of the concept of 'equivalent spherical diameter' (Odén 1916) or the diameter of a rounded particle which would behave in similar fashion to that fine platy particle. The use of this concept is general practice in the clay industry, where variations in particle size distribution have considerable effects on the physical properties of the clay and hence its use.

Until comparatively recently the most viable method for determination of particle size of ball clays was the Pipette Method of Andreason (1929). The particle size is calculated by Stokes' Law as the diameter of a sphere settling with the same velocity as the particles (principle of similarity in hydrodynamic behaviour). The method consists of withdrawing an aliquot from a suspension at a fixed level at stipulated times after settling has commenced. The assumption is that the sample contains only material suspended above the sampling point. The water is evaporated and the weight of the solid determined. From these weights and the time factors, a distribution curve can be computed. This method, although giving reasonable results, is tedious and long-winded in that the sample for the 1 micron point is taken 24 hours after settling commenced. As the preparation of the suspension is rigorous, a result is not available until the third day after commencement.

Recently, W.B.B. has purchased a Sedigraph 5000 Particle Size Analyzer developed by J. P. Olivier and G. K. Hickin of the Freeport Kaolin Company. This instrument measures the sedimentation rates of particles in suspension and automatically presents this data as a cumulative percent distribution in terms of Stokesian equivalent spherical diameter. The instrument determines, by means of a finely collimated beam of X-Rays, the concentration of particles remaining in suspension at various sedimentation depths as a function of time (Olivier, Hickin and Orr).
This instrument gives a size distribution curve in 20 minutes and represents a great step forward in fine particle measurement. All particle distribution curves reproduced in this thesis were measured by the Sedigraph 5000.

2.3. Commercially, for many years the behaviour of clays in suspension has been studied by the shaking-up of clay suspensions in a calibrated measuring cylinder and observing the effect. At low concentrations the particles fall independently of each other, the largest most quickly and the smallest most slowly, with the result that if the range of particle sizes is a large one the suspension remains cloudy for a long time and there is no sharp line of demarcation between suspension and clear liquid. At high concentrations the particles settle out 'en masse', the large particles apparently entraining the smaller. In this case there is a sharp line of demarcation between settling suspension and clear supernatant above (Pate, Noble and Clews 1953). Free (1916) reported that certain clay suspensions with 9% or more of solids settled with a 'line' but, for suspensions with a lower concentration, the supernatant liquid was cloudy. The 'line', whether distinct or indistinct, is generally known as the 'mud line'.

Using the line of demarcation (the mud line) as a means of measuring the rate of settling, Mischler (1912), Coe and Clevenger (1916) and Ralston (1916) have shown that most suspensions settle out at a uniform constant rate for a period, after which there is a fairly sharp alteration of the rate of settling, which then proceeds much more slowly. This phenomenon is observed in all the clays investigated. The first period, the settling period, is characterised by a comparatively rapid falling of the mud line and is terminated when the concentration reaches a point where
the particles interfere radically; further settling is controlled by packing characteristics and release of pore water. The rate of fall of the mud line then becomes very much slower and the second period of hardening commences. This continues at a diminishing rate over a very long period of time on a curve which is asymptotic to the final volume (Pate, Noble and Clews 1953). This technique is described and used by Pate, Noble and Clews (1953) and Federova (1966).

2.4. Settling or sedimentation of particles as fine as those in ball clay presents a problem. Odén (1916) states that a particle of 0.3 microns diameter requires 100 hours to settle through 10 cm of fresh water, and 14 months to settle 10 metres. Hazen (1914) studied the rate of settling for a full range of particle sizes with an assumed specific gravity approximating to quartz. The rates for particles of less than 20 microns were derived from formulæ and are reproduced in TABLE 2.2.

<table>
<thead>
<tr>
<th>Diameter of Particles in Microns</th>
<th>Rate of Settling in Millimetres per Second at 15°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.62</td>
</tr>
<tr>
<td>10</td>
<td>0.154</td>
</tr>
<tr>
<td>8</td>
<td>0.098</td>
</tr>
<tr>
<td>6</td>
<td>0.055</td>
</tr>
<tr>
<td>4</td>
<td>0.0247</td>
</tr>
<tr>
<td>2</td>
<td>0.0062</td>
</tr>
<tr>
<td>1</td>
<td>0.00154</td>
</tr>
<tr>
<td>0.1</td>
<td>0.0000154</td>
</tr>
</tbody>
</table>

From TABLE 2.2., a particle of diameter 1 micron would take about a week to settle 1 metre, a rate which would be neutralised by any current activity and, for smaller particles, would probably be neutralised
by Brownian movement. The cloudy nature of long-abandoned water-filled ball clay quarries testifies to this fact. As the finer ball clays are more than 50% less than 0.5 microns e.s.d., it is difficult to visualise an environment in which such a material has settled but, as such sediments exist, other factors must play a very important part.

The two most likely factors are:

(a) flocculation

and (b) evaporation.

The ultimate particle size of the ball clays is only achieved with the aid of a dispersant or deflocculant. FIG. 4.1. shows the particle size distribution of one of the carbonaceous ball clays dispersed with and without a deflocculant. The undeflocculated sample appears to be coarser indicating that the clay is slightly coagulated or slightly flocculated in the natural form. Olayinka Asseez (1970) found that the addition of a dispersant to natural lake water rather significantly altered the particle size distribution. Later in the same paper he concludes that settlement of the suspended sediments at the bottom of the lakes has been significantly aided by flocculation. The aggregation of finer particles into larger ones increases the settling velocity of the resulting particles. His next conclusion states "it is obvious that there are several causes of the observed flocculation due to various physico-chemical changes in the water. But the most important of them, particularly during the initial stages of impoundment when the decay of organic matter is considerable, is the release of organic acids resulting from this process". Although, as Asseez (ibid) remarks, there is little written on the subject, these facts have been well known in clay technology for many years. Although long string polymers and other complex compounds are now used as flocculants,
reducing the pH is usually sufficient to cause flocculation to some degree. In the case of the carbonaceous clays the natural pH is usually between 5 and 6 which is most certainly caused by the organic matter present which would have affected the sedimentation water in a similar fashion.

In clay technology, evaporation plays a large part in the dewatering of ball clay slips aided by absorbent plaster surfaces. Unlike china clay, the very fine ball clays are very difficult to filter press and the process takes a very long time so an evaporation process usually proves to be more effective. Chandler (1957) suggests from the plant remains that the climate at the time of deposition was probably warm. This suggests that evaporation may have played a very large part in the formation of the ball clays.

Teichmuller and Teichmuller (in Murchison and Westoll 1968) considered that the brown coal deposits of the Lower Rhine District of W. Germany were formed in a relatively dry period. These deposits are of approximately the same age as the Bovey Beds and are rich in Sequoia remains. The Bovey Beds are also very rich in Sequoia (Reid 1913 and Chandler 1957): Reid further suggests that "the plants are identical with species found in the well-known brown-coal deposits of Germany". A warm dry climate could well have facilitated evaporation as a sedimentological process in the formation of ball clays.

Best and Fookes (1970) showed some of the ball clays to be over-consolidated and put forward two possible explanations:-

(a) more intense desiccation shortly after deposition

and (b) pronounced secondary consolidation on a geological time scale.
They later conclude "from the geological field evidence, however, the authors are of the opinion that desiccation is the principal factor leading to overconsolidation of the Devon ball clays". From this evidence, it would appear that desiccation may well have been a prime agent of ball clay sedimentation but positive evidence, such as sun cracks, has not been found at Bovey, although such features are found, usually filled with silt, at Petrockstow.

2.5. On drying, the ball clays rapidly lose their structure and colour. Shrinkage cracks develop very rapidly and the specimens degenerate into a light grey powdery crumbled mass. It is necessary therefore to investigate techniques to preserve the material.

Techniques to preserve the original structure can broadly be divided into two:

(a) Peel Techniques
(b) Impregnation Techniques

Bouma (1969) devotes a chapter to each of these techniques, mainly with reference to unconsolidated sediments. Weatherhead (1940) used the pyroxylin peel technique in the study of clays and his observations led Williamson (1941) to use a comparable method for elucidating the effects of processing operations (filter pressing, casting, extrusion, mechanical spreading, etc.) on the arrangement of non-plastic particles in electrical porcelain and other ceramic 'bodies'. Weymouth and Williamson (1953) say "The pyroxylin films, peeled from dried specimens, were remarkable for bringing away with them clay layers resembling in thickness the usual type of petrological micro-section and similarly amenable to study with the polarising microscope".
The main disadvantage with pyroxylin peels is in the preparation of a perfectly smooth surface by dry grinding before application of the pyroxylin. If the microfabric of the clay is to be investigated such a method is of little use, since dry grinding inevitably re-orientates the particles of the surface layer. As the clay also requires drying, some of the structures are destroyed by shrinkage cracks.

Many natural and synthetic resins have been used as impregnating media, such as:

- Canada Balsam (Johannsen 1918 : Holmes 1921 : Keyes 1925 : van Straaten 1954 : Debyser 1957)
- Santolite M.H.P. Resin (Fowler and Shirley 1947)
- Marco Resin (Alexander and Jackson 1954 and 1955)
- Dammar Gum (Dalrymple 1957)
- Paraffin Wax (Goemann 1937)
- Castolite (Emery and Stevenson 1950)
- Polymethyl Metacrylate (Hagerman and Nyström 1952)
- Kollolith (Ross 1926)
- Celluloid (Schwarz 1929)
- Dental Cement (Silberminz 1923)

Other types of synthetic resins, which set irreversibly under the action of a catalyst, have been suggested by:

- Hallimond (1924 and 1925)
- Ross (1924)
- Scott Russell (1927)
- Schaffer and Hirst (1930)
- Day (1949)
- Ingerson and Ramisch (1954)
Catt and Robinson (1961), from which the foregoing list was derived, describe methods using Lakeside 70C and Araldite Resins. They also draw attention to methods described by Rowland and Lewis (1954) and Dalrymple (ibid) involving the use of Lakeside 70C dissolved in organic reagents such as ethanol or xylene, and Reineck (1958) using a synthetic Araldite Resin.

Mitchell (1956) developed a method for impregnating moist shale samples so that thin sections could be taken. He used samples that contained their natural moisture, since the drying effect on the fabric was unknown, but was chiefly concerned with the relation of the fabric of clays to their engineering properties. Tourtelot (1961) developed this method for geological use, using a high molecular weight polyethylene glycol compound known under the name of Carbowax.

2.6. Mitchell (ibid) recognised three important differences between a dispersed and a flocculated clay:

(a) At any consolidation pressure, a given weight of clay occupies a smaller volume in the dispersed (orientated) state than in the flocculated (random) state.
(b) The particles within a dispersed clay are distributed more uniformly throughout the volume than are the particles in a flocculated clay.
(c) A given increment of pressure applied to two clays, one dispersed and one flocculated, previously consolidated to the same pressure, causes a greater shifting of particles relative to each other in the flocculated clay than in the dispersed clay. This shifting is towards more parallel orientation.
The last premise is not thought to be relevant to the present problem but certainly (a) and (b) are relevant because they suggest a difference in orientation between a dispersed state and a flocculated state.

Mitchell later states "the optical properties of a randomly oriented group of particles are indeterminate. Such a group of particles appears uniformly grey when rotated in plane polarised light. If, however, the particles are aligned parallel to each other, they behave optically as one larger particle and have definite optical properties". Durrance (1967) describes a method for determination of preferred orientation in thin sections of crystal aggregates. If Mitchell's ideas are correct then theoretically it should be possible to determine whether a clay was deposited in a flocculated or a dispersed state. Meade (1966) generally agrees with Mitchell, although both authors are more concerned with the effects of pressure and compaction rather than flocculation. Meade introduced the idea of the particle domain formed during compaction. Within these domains orientation is perfectly preferred but the orientation is random between the domains. He also states that the existence of such a fabric in natural sediments is not proven, partly because it is not detectable by conventional optical methods or by X-Ray Diffraction methods.

2.7. The ball clays are in association with sand and lignite and, to a smaller extent, with the minerals marcasite and siderite. These two minerals are not found together but are common throughout the strata. The marcasite is generally referred to as 'mundic' in the clay industry and occurs as weird growths around seeds and twigs, often with a radiating structure, or as 'powder mundic' disseminated in the clay. Mundic occurs in all the clay types, but is probably more common in the carbonaceous clays.
Siderite is usually found in conjunction with the more siliceous clays and sands although not exclusively so. It occurs in two forms, either as a cementing agent in a sandstone, which is generally called 'sandrock', or as siderite spherules scattered throughout the clay. The 'sandrock' sometimes occurs in discrete bands, or sometimes as apparently concretionary boulders with small water-filled cavities at the centre, the boulders usually being found in limited areas on certain horizons.

Mason (1958), after Krumbein and Garrels (1952), devised a diagram which illustrated the relation between pH and oxidation potential and the geological materials on which they act. (FIG. 2.1.).

![FIG. 2.1. Sedimentary Associations in Relation to Environmental Limitations Imposed by Oxidation Potential and pH.](image-url)
In this diagram the concept of 'geochemical fence' is developed, a boundary which is defined by the presence of a particular mineral or material on one side and its absence on the other or, in effect, by a certain chemical reaction. From the diagram, the presence of marcasite would tend to indicate acid-reducing conditions and the presence of siderite almost neutral pH and a less reducing environment.

Curtis (1968) says "Analyses of the aqueous phase of sedimentary systems indicate that, as well as pH and EH variation, dissolved iron, carbonate, sulphur and silica species exhibit wide concentration ranges. In the past it has been usual for geochemists to represent equilibrium relationships between various iron minerals and dissolved species as two dimensional plots with EH and pH as variables". Garrels and Christ (1965) state, however, that "There is a tendency, for example, to represent relationships amongst iron carbonates, oxides and sulphides without regard to the values of eS and eCO₂ used for calculation". They believed that such disregard invalidated the use of such two-dimensional plots.

Curtis (ibid) later plots EH against Log activity HS⁻ or SO₄²⁻ and Log activity HCO₃⁻. Many of the conclusions drawn are irrelevant to the present study but his conclusions with regard to siderite are very important. Firstly, siderite is unlikely to be stable in any depositional water body. Secondly, he shows that siderite can be stable in the presence of maintained ferrous ion activities such as might be anticipated in sediment pore waters. Siderite is only stable therefore within sediment masses. Thirdly, in the absence of sulphate-bearing bacteria or in abiotic environments, siderite would be stable depending upon carbonate activity and the presence or absence of amorphous silicates. Fourthly, he concludes that the most likely environment for siderite growth is one of low EH (-0.25 to -0.35 volts), zero sulphide activity, severely restricted water circulation and positive carbonate activity.
Curtis unfortunately does not mention marcasite but concentrates on pyrite which he concludes is a metastable phase in anoxic water masses in which sulphide activities are maintained at non-equilibrium levels by bacteria. From FIG. 2.1., it could be deduced that marcasite forms under similar conditions, but with a lower pH depositional environment.
3. LITERATURE REVIEW OF THE SEDIMENTARY STRUCTURES WHICH EXIST IN CLAYS, SILTS AND SANDS.

3.1. As a basis for discussion, when discussing sedimentary structures, some classification is required. At present the nomenclature of sedimentary structures appears to be confused, and systematization is desirable. Boswell (1961) produced a diagram showing a relationship between rheological zones in clays, silts and sands, and the order in which they occur below the sedimentation surface (see FIG. 3.1). Elliott (1965) drew attention to these parameters and to how the rheological condition of a deposit is of great importance in determining its behaviour in response to the various forces operating at or near the surface of deposition.

![Diagram showing relationship between rheological zones](image)

Elliot presents a classification based upon the behaviour of deposits and the nature of the motions to which they are subjected. (see FIG. 3.2.).

Elliot uses two sets of parameters:

(a) Sediment Behaviour
(b) Nature of Operation.
### Fig. 3.2 A classification of subaqueous sedimentary structures. The displacement vectors represent simplified sediment or particle motions operating in connection with the formation of structures. The dotted lines adjacent to the vectors represent the sedimentation surface. Style of sediment behaviour is summarized in the second column.

<table>
<thead>
<tr>
<th>Nature of Operation</th>
<th>Exokinematic</th>
<th>Endokinematic</th>
<th>Biokinematic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sediment Behaviour</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquid</td>
<td>Grain by grain settling</td>
<td>Even laminae</td>
<td>Cross-stratification</td>
</tr>
<tr>
<td>Quasi-liquid</td>
<td>Formation en masse, dissolution of previous structures</td>
<td>Remnant sand-waves</td>
<td>Graded bedding</td>
</tr>
<tr>
<td>Hydro-plastic</td>
<td>Deformation and moulding, may be laked or cracked, no dissolution or crystallisation</td>
<td>Erosion ripples</td>
<td>Stretched-out ripples</td>
</tr>
<tr>
<td>Quasi-solid</td>
<td>Dislocation with concordant fault, well surfaces, tears apart, slight bending is possible</td>
<td>'Floating' slabs</td>
<td>Slide-bededding</td>
</tr>
<tr>
<td>Solid</td>
<td>Discordant fault, well, undeformed fault blocks, sharp erosion</td>
<td>'Put holes'</td>
<td>Slide-bededding</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tranquil Flow</th>
<th>Low-flow</th>
<th>High-flow</th>
<th>Translation Stumps</th>
<th>Transposition</th>
<th>Horizontal</th>
<th>Vertical</th>
</tr>
</thead>
<tbody>
<tr>
<td>grain settling</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>laked or cracce</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>slight bending</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Legend:
- Tranquil flow: Normal flow conditions
- Low-flow: Reduced flow conditions
- High-flow: Excessive flow conditions
- Translation Stumps: Depositional features
- Transposition: Subsidence features
Sediment behaviour can be sub-divided into five states:

(1) Liquid behaviour where particles are scattered, are non-cohesive and have complete freedom except for collisions between particles.

(2) Quasi-liquid behaviour where the particles are loosely packed but are unconfined, so that they can change their neighbours yet cannot move with complete freedom because of weak mutual attraction and dense spacing.

(3) Hydro-plastic behaviour (Shrock 1948, pp 152 and 259) occurs when the particles are less loosely packed and they are only able to revolve somewhat around their neighbours to such a degree that the whole mass can change shape, and yet are so confined or cohesive that they cannot change their neighbours, so relative movements during deformation are slight and distributed throughout the mass.

(4) Quasi-solid behaviour occurs where the particles are not firmly attached to each other but must, due to dense packing and close confinement, impede each other's movements to that movement can only be shear between the minimum number of grains.

(5) Solid behaviour is exhibited where particles are attached to each other and relative movement between them can only be achieved after fracture along a surface cutting the minimum number of bonds.

The boundaries between these styles of behaviour are "fences" in a similar manner to Krumbein and Garrels (1952) in their classification of mineral environments.
The classification by the second parameter, with respect to the nature of the operation, is less clear cut. Sedimentary structures may be grouped into three main classes according to the general location of the operation directly connected with the production of the structure.

(i) Exokinematic operations are defined by Elliot as "those in which the largest displacement vectors occur between matter outside the deposit and the unmodified deposit surrounding the structure produced". A similar but less precise definition may be movements occurring outside the unmodified deposit. This class of structure can be subdivided into three groups. Elliot, who was discussing subaqueous structures, maintained that this subdivision is based on the type of stream flow responsible for their formation - tranquil, low flow and high flow structures. This premise does not include exokinematic forces, such as cryoturbation, wind and differential loading (although this could be included in both low flow and high flow operations depending on the degree of differential loading).

(ii) Endokinematic operations are those in which the largest displacement vectors occur between some matter within that part of the deposit destined to form the structure, and the unmodified deposit. Such structures usually owe their origin directly to gravity or to a combination of gravity and earthquake shocks, and not via the medium of a body of water. Again, these definitions are after Elliot, who concentrated on
subaqueous sedimentary structures, and, taking no account of contemporaneous tectonics or authigenic structures, Elliott subdivides the endokinematic operations into translation or slump features, horizontal transposition and vertical transposition structures.

(iii) Biokinematic structures embrace trace fossils showing some modification of the original deposit.

Although only applied to subaqueous sedimentary features, Elliott's classification provides a useful basis for the classification of sedimentary structures, particularly with additions such as structures caused by differential loading, cryoturbation and tectonic movement. Elliott also states "the degree of freedom (of the constituent sediment particles) is that actually displayed at the time of production of the structure and not prior to or after its formation; hence thixotropic and dilatant phenomena need not be considered". As such phenomena are very difficult to identify, Elliott is probably justified in ignoring it. Commercially, however, the property of thixotropy is well known and exploited but, outside of this use, very little is written sedimentologically.

3.2 Liquid behaviour with grain by grain building produces two types of structure, both exokinematic, on Elliott's classification.

(a) Tranquil flow structures - even laminae.

Tranquil water refers to water bodies in which the bottom currents do not exceed the threshold necessary to move sediment particles resting on the bottom. In the case of fine clay particles this means virtually no movement. Three factors may influence sedimentation:
(i) the availability of aerial or aqueous-borne sediment
(ii) diversity of rates of sedimentation
(iii) competency of currents to retain some particles in suspension and allow others to sink.

Variations in these factors cause fluctuations in the composition of the sediment settling on the bottom, giving rise to laminae. Alternations of two compositions are common and variation in the sedimentation factors may be either sudden or gradual, so that either clear cut laminae or graded laminae accumulate. The best known example of this type of sedimentation is the varved clay with variations of lighter and darker materials dependent on seasonal variations. The literature on this type of sedimentation structure is large, including Wallace (1927), Fraser (1929), Rittenhouse (1934), Burwash (1938), Eden (1955).

(b) Low flow structures - cross stratification.
Low flow is characterised by standing eddies in response to form drag conditions (Bagnold, 1956). The eddies form a non-random pattern which is often imposed upon the surface deposit by gentle erosion, accretion or both simultaneously. Cross stratification would occur under these conditions and again has a prolific literature including McKee & Weir (1953), McKee (1957), Hamblin (1958), Wright (1959), Stewart (1961), Walker (1963), Allen (1963) and Elliott (1964).
3.3 Quasi-liquid behaviour, with formation en masse and dissolution of previous structure, has sedimentary structure classified as High Flow Exokinematic operations and the complete range of Endokinematic operations. Any original structures are destroyed when particles change their neighbours, thus "fossil" quasi-liquids are almost or entirely structureless internally and it is usually their external relationships which enable them to be classified.

Where high flow (exokinematic) permeates relatively deep into a sandy deposit, some sediment is carried into suspension and the topography of the sandy bed takes on the form of sand-waves. Bucher (1919) suggests that, under these conditions, the water-sediment boundary lies between two "liquids" of different viscosities rather than between liquid and solid, and that sand-waves are an example of Helmholtz boundary-waves. It appears that sand-waves are the result of quasi-liquid behaviour. Simons, Richardson & Albertson (1961) show that these structures are partially denuded as the high flow current declines and, in the laboratory flumes, relatively low relief sand-wave surfaces remain. Elliott classifies these structures as "remanié" sand-waves. The literature on the subject of sand-waves includes papers by Lane & Eden (1940), Langbein (1942), Bagnold (1946), Anderson (1953), Shinohara & Tsubaki (1959) and Jordan (1962).

Quasi-liquid behaviour includes structures in each division of the Endokinematic operations. Translation slump structures reveal evidence of significant lateral movement from the original sites of deposition. These structures are recognised by their exotic fossils, grading which becomes finer upwards, a mixed heterolithic texture, turbulent-like folding, a basal décollement (presumably this means a basal separation feature), a grooved rotational fault at the lower boundary, or by an aftermath deposit resting on the upper diastem.
boundary (Elliott, 1965). Quasi-liquid translation slumps include graded bedding (Kuenen & Migliorini, 1950, Kuenen 1952, Kuenen & Menard 1952 and Kuenen 1953) and slurried bedding (Wood & Smith 1959). This group generally is a continuous series between quasi-liquid and mainly solid end members.

Horizontal transposition structures appear to have been caused by penecontemporaneous lateral extension, contraction or shaking, more or less in situ. The structures in the quasi-liquid category lack any original stratification in the matrix. Two types of structure fall into this category, namely clastic intrusions, including the clastic dykes of Shrock (1948) and the "stone intrusions" of Raistrick & Marshall (1939) and auto-injection breccias including the "sliver beds" of Stewart (1963).

Structures having vertical or sub-vertical axes or axial planes, and showing evidence of dominant upward or downward transposition of sediments, are classed by Elliott as vertical transposition structures. In the quasi-liquid category is included sand volcanoes (Gill & Kuenen, 1958) and streamers, features which have structureless necks or cores.

Biokinematic structures are trace fossils involving some modification of a sedimentary deposit. Life however would be restricted in the quasi-liquid environment and traces cannot be recorded.

Williams (1960) showed that liquefaction of fine sands, silts, rock flour and thixotropic clays is possible involving the temporary transformation of the material into a very concentrated suspension. Williams referred to this as "Intra-stratal Flow", but was essentially referring to a hydro-plastic behaviour. Elliott says that hydro-plastic sediments are subject to deformation and moulding,
may be teased or drawn out, with no dislocation or dissolution.
Erosion ripples (Rippleartige Erosionsformen of Reineck, 1955) are
very likely produced by currents with standing eddies in a similar
manner to the normal accretionary ripples, but always in shallow water.
The literature on ripple marks is large and stretches back to the last
century, including papers by Hunt (1882), Darwin (1884), Gilbert (1884),
Bucker (1919), Evans (1941, 1942, and 1943), Liu (1957), Inman (1958),
Jopling (1961), Raudkivi (1962) and Ranga Raja & Garde (1964). Erosion
ripples and diastems are classified as low flow structures by Elliott.
Diastem, as defined by Barrel (1917), is a stratification surface
forming a break in a sedimentary seccession separating two strata and
transecting more than one lamina, by overstep or overlap, but which
cannot be shown to represent a gap in the succession equivalent to
more than one coset (a succession of related sets of laminae) or bed.

Where a high flow permeates into only the top one or two
centimetres of sandy sediment, the grains in the topmost layer become
orientated by flow (Dapple & Rominger, 1945) and surface streaming
gives rise to the primary current lineation of Stokes (1947) or part-
ing lineation of Crowell (1955). Such grain orientation is considered
by Elliott (1965) to be intermediate between quasi-liquid and hydro-
plastic behaviour.

Turbid high flow currents cannot permeate sandy sediments at
all but are capable of sculpturing muddy surfaces. Dzulynski &
Walton (1963) show that many structures, such as flute marks, long-
itudinal furrows, dendritic ridges and polished surfaces, depend on
turbidity currents, forming a series depending on the stage of the
current (e.g. flute marks result from the more vigourous proximal
stage, that is nearest the commencement of the turbidity current).
Filamental flow produces frondescent marks associated with furrows and
ridges. Both turbid and non-turbid high flow currents may operate to prod-
uce tool marks on mud surfaces. Literature on tool marks and associated
structures includes Peabody (1974), Cummins (1958), a discussion by Cromwell (1958) and a reply by Kuenen & Haaf, Hsu (1959), Craig & Walton (1962) and Dzulynski & Sanders (1962).

Both Kuenen & Menard (1952) and Sanders (1960) suggest that "streaked-out ripples" and convolute bedding (Kuenen 1953) are produced at least in part by drag from a turbidity current. Other authors on the origin and significance of convolute laminae include Haaf (1956), Williams (1960), Dott & Howard (1962) and Dzulynski & Smith (1963). Experiments were also described by McKee, Reynolds & Baker (1962) in the production of deformed cross-stratification.

All the foregoing are structures of Exokinematic operation in hydro-plastic sediments. Endokinematic translation slumps form a continuous series between quasi-liquid and mainly solid end members. In the hydro-plastic sediment behaviour classification translation slumps are represented by slurry slumps (slumps of Kuenen, 1949, and Allen, 1960).

Corrugated bedding and crumpled bedding with well defined laminae are placed by Elliott in the hydro-plastic compartment and at the quasi-solid fence respectively. Williams (1960) has described, under the term "convolute laminae", how lateral intra-stratal flow can produce folding of the corrugated bedding type. Allen (1960) describes the smooth U-shaped folding ascribed to corrugated bedding and irregular V-shaped folding of crumpled bedding. Vertical transposition features in an upward mode are represented by cusps (Selley, Shearman, Sutton & Watson, 1963) and small diapiric folds. These vertical transposition upward-moving structures form a series which ends in the mud lumps of Morgan (1961). The mud lumps of the Mississippi Delta are traversed by soft sediment faults, indicating sediment behaviour at the hydro-plastic to quasi-solid fence. In a downward mode would occur structures such as load marks and pouches (Macar, 1948, Kuenen, 1949).
Biokinematic structures in the hydro-plastic sediments are limited to surface traces of small animals. Some hydro-plastic deposits lie beneath a confining mass of quasi-liquid sediment and consequently do not form readily accessible habitats for animals. Where hydro-plastic sediments have thixotropic properties, with only a very thin quasi-liquid layer, "fossil" burrows can be found. Some surface travel traces may be left. Elliott (1965) draws from Reineck (1958) in his discussion of biokinematic structures.

3.5. The fourth type of sediment behaviour is quasi-solid, described by Elliott as "dislocation with concordant fault wall surfaces; tears apart; slight bending is possible". Only high flow of the exokinematic structures occurs. Slabs of mudstones or siltstone are found "floating" in the basal parts of both turbidites and non-turbid high flow deposits (Allen, 1960, 1963c). These "floating" slabs are probably plucked from the substratum by sub-vertical eddies or kolks.

Translation slumps are represented by slide-slump bedding including the fragmental beds of Wood & Smith (1959) with inclusions set in a vaguely laminated matrix, slide slumps (slumps of Jones, 1940; slumps with sliding of Van Straaten, 1949) with very little matrix between contorted sediments which displays some soft-sediment faults.

Horizontal transposition structures are confined to shredded bedding (Shirley, 1955) which consists of slightly folded fragments with acute edges (occasionally re-entrant), set in a matrix of minutely fragmented sediment sometimes dissected by a mesh of slickensides. This structure is characterised by relict stratification seen within fragments and also across the whole, due to the fragments retaining their original relationships to a large degree.

Vertical transposition structures in quasi-solid are represented by
guilielmites, which are interpreted by Wood (1953) as collapse structures around fossils. They occur in muddy sediments and are characterised by small polished slip-surfaces arranged around the fossil.

Guilielmites could be argued to be biokinematic in origin. Quasi-solid sediments are readily burrowed or otherwise structurally modified by life activity, and trace-fossils produced in these sediments are recognisable by their contact annuli (the zones of dragged original laminae adjacent to the trace core). Life activity is sometimes so great as to produce more or less structureless bioturbation.

3.6. The final category of Elliott is solid sediment behaviour, with discordant fault walls, undeformed fault blocks and sharp erosion. Exokinematic structures are represented by "Pot Holes", caused when fast turbulent streams develop sub-vertical eddies (known as "kolks") which erode pot holes in a solid stream bed with the help of pebbles or even boulders swirling around in the excavation. The final end members of translation slumps are the slide-beds or sub-aqueous slides of Kuenen (1956) which contain solid blocks and rest on rotational faults.

Horizontal transposition features are represented by "jumbled block" structures including "lurching" of Lawson (1908) and the sand-siltstone blocks separated by curved faults or shredded mudstone envelopes described by Shirley (1955). Richter (1958) describes "lurching" as a distinctly earthquake type effect due to shaking of superficial deposits produced by wave propagation. The relationships of Shirley's structures show that they are also superficial and Richter refers them to an earthquake origin.

Indurated rock is usually excavated by animals for habitation, the resulting biokinematic structures having clear-cut walls. The arcuate layer structure produced in burrow cores, when animals pack loose material
behind themselves as they progress up or down (Reineck, 1958), are not laminae in the sense in which it has been used previously, even though they may resemble laminae in the surrounding deposit.

3.7. Elliott confined himself to sub-aqueous structures, but other modifications obviously occur. Van Houton (1964) describes sedimentation in short asymmetrical "detrital" and "chemical" cycles that resulted from expansion and waning of a lake due to variations in climate. The mudstones of the detrital cycle have a small scale contorted fabric produced largely by crumpled shrinkage cracks and borrows. Mudstones in the chemical cycles are brecciated on a microscopic scale, which Van Houton considers to be due to syneresis (the spontaneous expulsion of liquid from a gel). Van Houton recognises two types of shrinkage cracks:

(i) subaerial
(ii) due to syneresis

Freshney & Fenning (1967) draw attention to sun cracks, usually filled with silty sand, in some of the clays of the Petrockstowe (North Devon) Basin, some of the cracks being over 4 feet deep.

Moore & Scruton (1957) investigated minor sedimentary structures in shallow water Gulf of Mexico sediments. Deposits of the Mississippi Delta and along the Texas coast can be divided into:

(i) regular layers (thin beds or laminations)
(ii) irregular layers (rough or crude layers and lenses)
(iii) mottles (discontinuous lumps, tubes and pockets)
and (iv) structureless homogeneous sediments.

The different types of structures are formed on or near the depositional surface, contemporaneous or nearly contemporaneous with deposition.
The differences between depositional environments, which produce the various structures, are differences in:

(a) sediment sources
(b) physical processes and their intensities
and (c) rate of deposition.

Regular layers are characteristic of areas of rapid deposition and relatively few bottom-living animals (Tranquil Flow Exokinematic of Elliott, 1965). Irregular layers and mottles are formed by bottom-living animals altering existing sediments (Bioturbates of Elliott). Homogeneous deposits are either primary or secondary, formed by extremely rapid deposition, uniform deposition or by complete secondary re-working. The latter deposits, that is sediment with no visible internal structure, are very significant. Structureless, homogeneous deposits are often primary and are usually the products—either of a very high rate of deposition which reduces the time available for secondary alteration or of a moderate depositional rate where source materials do not contract in texture or composition. The fine-grained deposits are attributed to an environment over 120 feet deep, with coarser-grained homogeneous sediments from 30 feet to 90 feet in depth. Moore & Scruton (1957) build up a classification of processes that form most minor internal sedimentary structures. (FIG. 3.3.).

3.8. Another form of structure, which may well be confused with normal sedimentary structures, is that of cryoturbation. Although periglacial conditions did not occur contemporaneously with sedimentation, such features certainly exist in the Bovey Basin (Dineley, 1963). These structures do not however extend in depth, and can be discounted at depths of more than 30 feet (10 metres) from the pre-Pleistocene surface.
<table>
<thead>
<tr>
<th>TYPE</th>
<th>WHERE FORMED</th>
<th>PROCESS OF FORMATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>REGULAR</td>
<td>PRIMARY formed at time of initial deposition</td>
<td>ONE MAJOR SOURCE</td>
</tr>
<tr>
<td>LAYERS</td>
<td>SECONDARY alteration of initial deposit</td>
<td>TWO OR MORE SOURCES</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fluctuations in size of material transported and deposited</td>
</tr>
<tr>
<td>IRREGULAR</td>
<td>PRIMARY</td>
<td>Winnowing resulting from suspension by currents - organic activity resuspending sediments</td>
</tr>
<tr>
<td>LAYERS</td>
<td>SECONDARY</td>
<td></td>
</tr>
<tr>
<td>DISTINCT</td>
<td>PRIMARY</td>
<td>Fluctuations of size of material deposited on irregular bottom</td>
</tr>
<tr>
<td>MOTTLES</td>
<td>SECONDARY</td>
<td>Organic activity resuspending sediment with winnowing of fines. Local slumping.</td>
</tr>
<tr>
<td></td>
<td>PRIMARY</td>
<td>Open animal burrows or surface irregularities filled with contrasting material</td>
</tr>
<tr>
<td></td>
<td>SECONDARY</td>
<td>Burrowing organisms disturbing layered deposit</td>
</tr>
<tr>
<td></td>
<td>PRIMARY</td>
<td>Occasional soft clay balls</td>
</tr>
<tr>
<td></td>
<td>SECONDARY</td>
<td>Partial destruction of earlier formed layered or distinctly mottled structures by crawling organisms</td>
</tr>
<tr>
<td>HOMOGENEOUS</td>
<td>PRIMARY</td>
<td>Deposition of uniform sediment or at a very high rate</td>
</tr>
<tr>
<td></td>
<td>SECONDARY</td>
<td>Total destruction of minor internal structures by burrowing organisms with complete sediment mixing</td>
</tr>
</tbody>
</table>

**FIG. 3.3.** Classification of Sedimentary Processes - After Moore and Scruton (1957).
4. TECHNIQUES USED AND DEVELOPMENT.

4.1. The moisture content of clays has been discussed by many authors. Grim (1953) pointed out that the water lost at low temperatures (defined as prolonged heating to about 100°C - 150°C) probably belongs to three categories:

- **(a)** the water in pores, on surfaces and around the edges of discrete particles of the minerals
- **(b)** in the case of vermiculite, montmorillonite and the hydrated form of halloysite, the water between the unit-cell layers of these minerals
- **(c)** in the case of sepiolite - attapulgite - palygorskite minerals, the water which occurs within the tubular opening between the elongate structural units.

The clays under consideration are kaolinitic and are of a type to which only (a) applies. Water of Category (a) comes off with very little energy required, which is an advantage as an easy method of moisture determination, but a disadvantage in sampling. Because of the ease of moisture loss, samples have to be taken immediately from a freshly cut face or core, and tested without delay to ensure no error due to moisture loss. Two methods are employed:

- **(i)** An accurate method based on weighing the moist sample, drying the moist sample at 100°C for 12 hours, allowing the dried sample to cool in a desiccator and reweighing the dried sample. The moisture content is then the loss in weight expressed as a percentage of the wet weight.
A more rapid but less accurate method taking about 15 minutes to perform. This involves an infra-red lamp and a counterbalanced scale pan with an attached pointer moving across a calibrated scale. The scale pan is loaded with the chopped sample until the pointer reaches zero, at which point the scale pan contains 10 grammes. The infra-red lamp is turned on and the loss in weight is directly registered on the scale as a percentage of the wet weight. Although this latter method is rapid, the error may well be in the order of 5% relative. The latter method would only be used when a rapid result is required on a very limited number of samples.

The moisture content is dependent on a number of factors, including:-

(a) Mineralogy
(b) Particle Size Distribution
(c) Depth of Burial
(d) Desiccation

The mineralogy and particle size are reflected in the chemical analysis and, in particular, in the SiO₂ content. This relationship was investigated by taking samples from the working faces of opencast workings and obtaining moisture contents by the accurate method. The indications showed more or less straight line relationships between silica content and moisture. To investigate the relationship with depth, samples from a number of boreholes in a boring programme were analysed for moisture by the accurate method and the results correlated with level* and SiO₂.

*Standard procedure is to refer levels to a datum of 1000 feet below Ordnance Datum, thereby avoiding negative levels.
4.2. As the depth of burial increases, the moisture content would be expected to decrease, and the particles become more closely packed. The latter trend implies that the bulk density of the clay should increase with depth. As the variation is likely to be small, the sampling points would require large variations in depth. Such samples could only be acquired from boreholes. As all boring samples are dried and jaw crushed, previous boring samples are useless for investigating moisture content. All samples have to be tested before correlation can be attempted with any degree of accuracy and selected samples can then be used for investigating bulk density, albeit in a dried form. One seam, along one section line, was chosen for investigation and the relevant samples were withdrawn from the sample library. Lumps of clay of various sizes were selected and their bulk densities determined on a Doulton Bulk Density Balance. This apparatus is shown in Plate 4.1.

PLATE 4.1. Doulton Bulk Density Balance.

The selected piece is weighed and the amount of mercury displaced by the piece is weighed. The bulk density is then computed from:-
Bulk Density = \frac{\text{Weight of Piece} \times \text{Density of Mercury}}{\text{Weight of Mercury Displaced}}

Accurate correlation was required to avoid changes in lithology which would drastically affect the bulk density. Small changes in lithology within a seam, such as slight changes in silica content or carbon content, would be expected to produce considerable scatter but, nevertheless, general trends should be discernible. The main difficulty encountered in carrying out the investigation was partly due to minute variations in lithology and partly due to the size of the samples. Eight to ten separate pieces were used from each sample but unfortunately the crushed samples in store consist of rather small lumps, with possibly some slight variations in lithology from lump to lump. The pieces selected were as large as possible but a certain amount of variation was still encountered.

4.3. The Sedigraph 5000 Particle Size Analyzer was utilised in all particle size determination. The usual method is to mix a suspension at 8% solids (slurry density 1.049) with the addition of 4% 1:1 sodium hydroxide/Calgon as a deflocculant (or dispersing agent). The analyzer plots the cumulative distribution curve directly onto log graph paper, from which relevant size fractions can be read. This distribution is referred to as the dispersed or ultimate particle size distribution.

In practice, with no dispersing agent added, the clay assumes a different, apparently coarser particle size distribution. This difference between the natural and ultimate particle size distribution curves is probably caused by flocculation during sedimentation. Although, commercially, the ultimate particle size distribution is the more important, sedimentologically the natural particle size distribution has more relevance. The two distributions, on samples of a carbonaceous clay, are illustrated in FIG. 4.1. and TABLE 4.1.
Schofield & Samson (1954) show that kaolinite crystals are negatively charged but that parts of their surfaces, probably the edge faces, are positively charged. The attraction of the positive charge on the edge faces for the negative charges in the body of the crystals is regarded as the cause of flocculation which occurs in the absence of salt. The fresh water probably slightly acid conditions under which the clays are presumed to have been sedimented would fulfil these conditions, and hence the clays were sedimented in flocculated form.

Once the particles reach a certain size or concentration, interference between particles is high and relative movement between particles of differing sizes is low and the whole settles out 'en masse' without any grading. The Sedigraph shows a flocculated material, firstly by an apparent coarsening of the particles and, secondly, as the flocculation increases, by a characteristic curve. The particles settling 'en masse' are at similar concentrations at all positions below the mudline and a straight line at 100% results until the mudline is crossed by the scanner, at which point there are no particles, and the curve drops vertically. Before complete flocculation, the supernatant is not completely clear and some grading does occur, so the curve is nearly horizontal initially and not completely vertical after traversing the mudline. Recognition of flocculation becomes readily apparent. A similar curve would be

<table>
<thead>
<tr>
<th>% less than e.s.d.</th>
<th>NATURAL</th>
<th>ULTIMATE</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 µ</td>
<td>90</td>
<td>96</td>
</tr>
<tr>
<td>10 µ</td>
<td>83</td>
<td>93</td>
</tr>
<tr>
<td>5 µ</td>
<td>77</td>
<td>88</td>
</tr>
<tr>
<td>2 µ</td>
<td>66</td>
<td>80</td>
</tr>
<tr>
<td>1 µ</td>
<td>57</td>
<td>72</td>
</tr>
<tr>
<td>0.5µ</td>
<td>40</td>
<td>53</td>
</tr>
</tbody>
</table>

TABLE 4.1. Particle Size Distributions - Carbonaceous Clay.
expected from slurries above certain concentrations; with no grading and clear supernatant when particles are settling 'en masse'.

Particle size distributions were carried out on a number of selected samples. Further to this, the variation of particle size was investigated within the seams. This was done on the basis of two modes:

(a) variation within seams.
(b) the variation in a core sample.

The variation was checked in individual seams. As many samples as possible were taken from:

(1) a slightly carbonaceous seam in a quarry
(2) a non-carbonaceous slightly siliceous seam from one of the underground mines

and (3) a slightly carbonaceous seam in a quarry location.

The particle size variation in these seam samples was investigated.

The variation of particle size distribution in a core sample was carried out on a 5-inch core stick, nine ½" samples being taken normal to the dip, with distribution curves being carried out on the samples. Unfortunately it was not possible on the core chosen to determine which was the top and the bottom of the core. The core chosen was a sample of the carbonaceous clay on which most of the initial tests were made.

4.4. The settling technique described in Chapter 2.3. and the effects of dispersing and flocculation (by variation of pH) were investigated. The initial test was to investigate the settling
characteristics at ultimate particle size distribution. The usual carbonaceous clay was used. 250 ccs of slurry at 8% solids was mixed with the addition of 4% 1:1 sodium hydroxide/Calgon as a dispersing agent. The resultant slurry was allowed to settle in a 250 cc measuring cylinder and the results observed, recorded and plotted in graph form.

The settlement of the same clay was then observed at various levels of flocculation. This was achieved by varying the pH by additions of dilute sulphuric acid. The carbonaceous clay was dispersed by blunging, and the density of the resultant slurry adjusted to 8% solids on a weight/weight basis. This slurry density was adopted because this is the density at which the Sedigraph operates. It was thought unlikely that a natural slurry would reach 8% solids, except under turbid conditions but that density is low enough not to cause excessive interaction and interference between particles. Although the starting density may seem important, it must be remembered that the suspension is settling all the time and that the slurry density under the mudline is increasing until a 'critical level of concentration' is reached (the term 'critical concentration' is avoided as, in the clay industry, this latter term has a particular meaning and, although the two terms may be related, they should not be confused) when the larger particles entrain the finer particles and the rate of fall of the mudline decreases sharply. Provided the critical level of concentration has not been reached for that particular clay, the starting density was not thought to be important. As it was considered impossible other than to guess at the natural sedimentation slurry density, which was probably very variable anyway, the most convenient slurry density of 8% solids was chosen. The natural pH of the slurry was then taken with a direct-reading pH meter. Five calibrated 1000 cc measuring cylinders were filled with the blunged slurry and the pH of the contents of four of
these tubes was reduced progressively by increasing additions of dilute sulphuric acid. The tubes were then allowed to settle for 12 to 16 hours; they were then shaken to disperse the particles again, and the time and date recorded. The 'mudline' and nature of the supernatant were then recorded at various times, from which curves could be prepared to represent the settling behaviour of that clay. The settling trials were carried out on four samples:

(a) a carbonaceous clay
(b) a siliceous clay
(c) a low silica non-carbonaceous clay
and (d) a very carbonaceous clay.

When the curves had been obtained, the effects of variation in concentration appeared to be more important than had been previously considered. Variation in concentration was investigated by mixing cylinders of the natural pH at varying levels of concentration. The mudlines and nature of the supernatant were recorded in the same way at varying times, and curves prepared. These tests could not be carried out on core samples because of the amount of sample required. The four clays tested were all from the normal working sequence and cover the range of the different types of clay, except for carbonaceous siliceous clays, which are not found in the working sequence but only in core samples.

4.5. The chemistry of the clays at first sight has little to do with the physical or sedimentological characteristics of the material. On further inspection, chemical analysis is found to be of considerable use and relevance (e.g. moisture content shows fair correlation with silica content). The chemistry of the material reflects the mineralogy: silica is indicative of free quartz, alkali content \((K_2O + Na_2O)\) is indicative of mica content and loss on ignition of carbon content. The old wet chemistry
methods of chemical analysis based on colorimetry were laborious, involving considerable use of laboratory space and labour. Rapid chemical analysis of WBB samples is carried out by the X-ray Fluorescence technique using a Philips PW 1220 Semi-Automatic X-Ray Set.

In the X-Ray Fluorescence technique, the sample is irradiated with primary X-Rays produced from the X-Ray tubes. These impinge on the sample, and secondary or fluorescent radiation is produced. Secondary radiation consists of X-Rays from the elements present in the sample, each of which has a number of forms of different wavelengths. When the secondary radiation is presented to the analysing crystal via a collimator each form is diffracted through an angle according to its wavelength. The angle for any particular wavelength of radiation (given by the Bragg equation $n\lambda = 2d \sin \theta$) is set on the goniometer. Thus it is possible to count with a detector one particular form (e.g. SiKα or AlKα, etc.) by setting the goniometer and counting on that wavelength. With the Philips PW 1220 Semi-Automatic X-Ray Set, it is possible to programme the pre-set conditions (i.e. X-Ray tube, goniometer angle, collimator, analysing crystal, detector) for any element except those for which the excited radiation is so soft that it cannot be adequately detected, i.e. those with atomic numbers less than fluorine (hydrogen, helium, lithium, Beryllium, boron, nitrogen and oxygen). Programming the equipment not only saves time but ensures that the machine is always counting on the peak for each element. Machine drift, one of the causes of inaccuracy in X-Ray analysis, is automatically compensated for by the use of a standard which is analysed once in every three samples. The concentrations of the elements in the samples are calculated by computer from the total counts minus the background counts after comparison with standard curves or, as in this case, by using a ratio of standard counts to sample counts and comparing to appropriate curves. Any machine drift is taken into account by the machine standard.
The major errors in X-Ray Fluorescence analysis are matrix effects such as mass absorption and particle size. The customary method of avoiding matrix effects is to dilute and fuse. As this is time-consuming, the problem of particle size error, and a further source of error in mineralogical variation, is minimised by simply dry grinding the specimen and subsequent use of close calibrations (i.e. comparing like with like).

The dried sample is first ground in a Tema Mill for a fixed period of time to pass through a 300's mesh sieve (53 microns). A disc of the material is pressed at 10 to 11 tonnes per square inch. Three such discs together with a standard disc make up one programme which takes about 30 minutes to complete. The print-out then gives SiO₂, TiO₂, Al₂O₃, Fe₂O₃, CaO, K₂O, MgO, Na₂O, for which the WBB machine is generally set up. Subtraction of the total from 100% gives a good approximation of the loss on ignition. If greater accuracy is required for the latter, a separate loss on ignition has to be performed. The ground and weighed sample is heated in a muffle furnace for 4 hours at 1000°C, followed by careful cooling and desiccation before reweighing. The loss on ignition is calculated from the loss in weight at 1000°C as a percentage of the original weight of the sample. This change in weight is caused mainly by loss of combined water and burning off of carbonaceous material. A further elaboration could be achieved by use of a Stanton Thermobalance, which gives a trace showing the temperature at which each loss in weight occurs. In practice, the majority of the samples tested have had the loss on ignition calculated by difference.

As well as providing parameters for comparison with other properties, titania and iron show interesting trends with relation to silica and provide some insight into the sedimentology of the Bovey Basin.

4.6. Mineralogical investigation of clays is carried out by X-Ray Diffraction equipment.
Diffraction of X-Rays by a single crystal has been known since the pioneer work of Van Laue in 1913. The first X-Ray Powder Diffractometer was developed by Le Galley (1935). Since then the technique has become widely used for both qualitative and quantitative mineralogical analysis.

When a beam of monochromatic X-Rays falls on a crystal lattice (a regular periodic arrangement of atoms) a diffracted beam will be produced in certain directions. It is necessary that the waves diffracted by the individual atoms be in phase in the direction of observation and it can be shown that for ultimate reinforcement the condition given by the following equation must be satisfied:

\[ 2d \sin \theta = n\lambda \]

where

- \( d \) = interplanar spacing
- \( \theta \) = angle the beam of X-Rays makes with the crystal plane
- \( \lambda \) = wavelength of the X-Rays
- \( n \) = an integer

A full treatment of the subject of X-Ray Diffractometry is outside the scope of this thesis but details of the theory are given in Klug & Alexander (1962).

The principles of diffraction are the same for all units but there are slight differences in the details of operation. X-Ray Diffraction apparatus gives a pattern of the principal crystallographic planes that cause the diffraction of X-Rays and hence, by interpretation, gives the actual minerals that are present in a mixture.

The instrumentation required for X-Ray Powder Diffractometry consists of three basic parts:
A source of radiation, consisting of X-Ray tube and stabilised high voltage generator (in this case a Philips PW 1010).

(2) A Diffractometer.

(3) A Detector, counting and recording equipment.

The function of the generator and X-Ray tube is to give a stable source of radiation. FIG. 4.2. shows the geometry of a typical diffractometer. It is typified by a diverging beam from a line source F, falling on the specimen S, being diffracted and passing through a receiving slit R into the detector. The amount of divergence is determined by the effective focal size at D which is matched with the scatter slit SS. The scatter slit in combination with the receiving slit reduces the scatter of the detector. Lateral divergence is controlled by two sets of parallel plate vertical collimators P and RP placed between the focus and specimen and between scatter slit and receiving slit respectively. The function of the detector is to convert the individual X-Ray photons into voltage pulses which are counted and integrated by counting equipment giving various visual indications of X-Ray intensity. The results are displayed on a continuous chart recorder which plots intensity of radiation against values of 2θ as the detector traverses a predetermined range of diffraction angles.

'Unoriented' mounts are utilised with WBB equipment. The sample is first ground for 20 seconds in a Tema Mill, and then packed into an aluminium holder. When the hole in the mount is filled, it is pressed down lightly with the blade of a knife or spatula to obtain the necessary flat surface which coincides with that of the surface of the aluminium holder. A typical diffraction trace of a disordered kaolinite ball clay is shown in FIG. 4.3.
Fig. 4.2 The X-ray optical system of the Phillips goniometer
(Parrish, Hamacher, Lowitzsh, Philips Tech. Rev. 15, 125, 1954)
FIG. 4.3. X-Ray Diffraction Trace WBB 5008 - A Disordered Kaolinite Ball Clay.
The dominant minerals present in ball clays are kaolinite, a micaceous mineral and quartz. Minor amounts of other minerals, in addition to carbonaceous matter, are often found in association with these major components. These minor minerals may include tourmaline, felspar, chlorite, montmorillonite, interstratified clay minerals, various titanium compounds (such as anatase, ilmenite and occasionally rutile) and various iron minerals, such as siderite and marcasite (which are fairly common), pyrites, limonite and haematite. For general purposes, ball clays can be regarded as an idealised ternary system consisting of kaolinite, mica and quartz. The kaolinite component of the ball clays is of the type referred to as 'b-axis disordered kaolinite' (Brindley & Robinson, 1946). Kaolinite consists of sheets of SiO₂ tetrahedra bonded to sheets of Al₂O₃ octahedra that are continuous in the a and b directions and stacked one above the other in the c direction. Well crystallised kaolinites on a diffraction trace of unoriented mount show peaks at 7.15 Å (001) face, 3.57 Å (002) and a series of reflections between 3.37 Å and 2.55 Å caused by hkl's (111) - (201). The structure of a disordered kaolinite is similar to well crystallised kaolinite but is disordered principally by random layer displacement parallel to the b axis (Hinckley, 1962). Hinckley investigated the crystallinity of the hard and soft kaolins in Georgia and South Carolina. 'Hard' and 'soft' describe the ease of pulverising the two different types of kaolin found in these commercial kaolin deposits. The hard kaolin was sedimentoed in a marine environment and the original detrital kaolin was not recrystal­lised. The soft kaolin was sedimentoed in a fresh water environment and the detrital kaolinite was leached and recrystallised. Hinckley further showed that the hard kaolinites had better crystallinity than the soft kaolinites, and a method for distinguishing well crystallised and poorly crystallised kaolinite was worked out. Hinckley used the 110 and 111 reflections of kaolinite at 20.4° and 21.3° 2θ (CuKα radiation) to measure the crystallinity. The method of measurement is shown in
FIG. 4.4., which shows a well crystallised kaolinite. From the diagram, the Crystallinity Index is \( \frac{A + B}{C} \). It is noticeable that a broad reflection in the vicinity of 4.48 Å (19.8° 2θ) occurs in a disordered kaolin (see FIG. 4.3.) whilst a number of sharp reflections in the same vicinity occur for an ordered kaolinite. On Hinckley's scale, a degree of crystallinity of zero represents completely disordered kaolinite, whilst a degree of crystallinity of approximately 1 represents reasonably well ordered kaolinite (Stentiford & Mitchell, 1973).

\[
\text{Cryst. Index} = \frac{A + B}{C}
\]

![Crystallinity Index Calculation](image)

FIG. 4.4. Calculation of Crystallinity Index.

Theoretically, the Crystallinity Index can reach 2 but, in practice, the Index rarely exceeds 1.3.

When this technique is applied to the ball clays from the South Devon deposit, a range of values from approximately 0.1 to approximately 0.9 has been obtained. The range of values obtained from clay of the North Devon deposit is much narrower (less than 0.1 to 0.3). None, however, possess well ordered characteristics (Stentiford & Mitchell, 1973).
The derivation of numerical values of crystallinity is complicated by the presence of mica. In addition to the structural disordered referred to above, isomorphous substitution is known to occur within the kaolinite lattice. The most common substitution which occurs is that of iron and possibly magnesium replacing aluminium in the octahedral layer of the kaolinite which results in a charge imbalance which affects such properties of the clay as its cation exchange capacity. Examination of the X-Ray Diffraction patterns of such substituted kaolinites, and comparison with relatively unsubstituted kaolinites, such as those associated with hydrothermal kaolins of the china clay type, shows a broadening of the basal (001) reflections with some 'tailing' of the diffracted peak towards a shorter "d" spacing. Whilst some of this effect may be explained by the smaller particle size and lower crystallinity of the kaolinite in the ball clays, the amount of broadening generally observed is too high to be accounted for by these factors alone.

In general, kaolinites in the X-Ray Diffraction traces used in this thesis are described as well ordered, medium ordered, disordered or highly disordered. The significance of the order/disorder relationships will be discussed in Chapter 6.7.

Ball clays contain recognisable amounts of micaceous minerals. The broad peaks observed from the basal reflections of the micaceous minerals are shown in FIG. 4.3. The broadness of these basal reflections is not inconsistent with a high degree of lattice substitution, probably of iron for aluminium, and the mica also contains a deficiency of potash somewhat compensated for by an excess of lattice hydroxil ions (Stentiford & Mitchell, 1973). It is likely that this mineral is of the type sometimes termed 'hydrous mica' (Brown & Norrish, 1952), or 'illite' (Grim, Bray & Bradley, 1937). This mineral has a very similar particle size distribution to the kaolinite with which it coexists so therefore it is not possible to separate a pure sample of the material to characterise
completely the chemical and physical properties of the mineral. A further complication exists where there has been occasional evidence from X-Ray Diffraction that there may be more than one type of micaceous mineral present. Stentiford & Mitchell (1973) suggest that these minerals may in fact be of the illite type plus a small amount of detrital mica carried virtually unaltered from the Dartmoor granite mass. In the X-Ray Diffraction traces carried out for this thesis, this mineral is merely described as mica, and as comparatively high, medium or low in quantity.

The third main component of clays, quartz, also shows numerous reflections on X-Ray Diffraction. Considerable evidence exists to show that quartz occurring in the ball clays may be considered to be a mixture of crystalline quartz and amorphous silica. It is likely that the amorphous component exists in part as a coating on the surface of the crystalline grains of quartz as suggested by Nagelschmidt, Gordon & Griffin (1952) and Gordon & Harris (1955), since treatment with hydrofluoric acid, which dissolves this amorphous surface layer, increases the intensity of the X-Ray reflections from the quartz grains.

Stentiford & Mitchell (1973) say "from our own work, we believe that the free silica which exists in the clay-sized fraction of the South Devon clay consists of 60-65% macrocrystalline quartz and 35-40% amorphous or cryptocrystalline silica". It is relatively easy to determine the amount of quartz which is present in a ball clay by means of X-Ray Diffraction and the quartz is described quantitatively as amorphous and crystalline. The significance of this division of free silica is obscure and could well be a field for further research.

Montmorillonite is an influential impurity in ball clays and detection is usually made by X-Ray Diffraction on oriented specimens.
However, montmorillonite is a very poor reflector of X-Rays and it is difficult to identify this mineral when it occurs at levels less than 5%, but often minor changes in the diffraction pattern can be seen which makes it possible to infer the presence of quantities as low as 2-3%. The structure of montmorillonite is similar to that of mica but the former has interlayer water instead of K⁺ ions between the layers; there is little bonding and macroscopic crystals are not formed. On 'unoriented' mounts weak hk reflections are found but the principal reflection is from the (001) basal plane between 12 Å and 15 Å. Atschuler & Dwornik (1963) suggested that montmorillonites have been formed from the breakdown and weathering of micaceous compounds in the country rocks under alkaline conditions. Various intermediate stages in this formation have been suggested including vermiculite, illite and mixed layer intergrowths of both. Some indirect evidence for the occurrence of small quantities of interlayer minerals in the South Devon clay is provided in Best & Fookes (1970) who compared the mineralogy of Stoneware and Whiteware clays based on the Schultz (1964) technique. In the ceramic industry, the common method employed to derive quantitative mineralogical compositions is the so-called 'Mica Convention Rational Analysis'. By this method mineralogical compositions are estimated from chemical analyses as follows: the soda and potash contents are used to calculate the amounts of theoretical paragonite (soda mica) and muscovite (potash mica); the alumina which then remains is assigned to kaolinite, and any excess silica is accounted for as quartz; any excess loss on ignition is quoted as 'carbonaceous matter'. This method has many drawbacks, such as the assumption that the kaolinite is pure, that the micaceous mineral is a mixture of ideal muscovite and ideal paragonite (instead of the deviation from the idealised formulae of hydrous mica) and the presence of other alumino-silicates, such as tourmaline and felspar, is discounted. Although it is recognised that rational analysis is of limited value, the few methods which do exist for the quantitative measurement of clay
minerals by X-Ray Diffraction are very time-consuming in preparative work (up to six hours per sample) and, even then, have a low reproducibility and are of limited reliability.

Very little of the free iron which occurs naturally in ball clay is accounted for by iron compounds, such as marcasite, pyrites and siderite, or that associated with organic matter. The majority of the 'free' iron present is in the form of hydrated oxide (e.g. limonite) which occurs as a coating on the individual crystallite of kaolinite, mica and quartz. The iron also occurs as an isomorphous substitution within the lattice of the kaolinite and mica. Only the compounds can be detected readily on X-Ray Diffraction.

The average level of TiO₂ in the ball clays is about 1%, the principal form being anatase, the presence of which is readily detected in X-Ray Diffraction. Rutile is found on rare occasions.

4.6.7. All the techniques so far described investigate the behaviour of particles and the nature of particles and most involve the breaking down of the naturally occurring material. To study the structures as they naturally occur necessitates preservation of the sample at its natural moisture content so that it can also be sliced, ground and polished. The impregnation and thin sectioning of various types of friable rock, soil, etc., have been described by many authors. Comparatively few writers, however, have described the impregnation of clays which presents a particular problem in that many of the resins usually used with coarse sediments are too viscous to penetrate the relatively small pore spaces of finer materials. Mitchell (1956) developed a method which involved the replacement of soil moisture with a high molecular weight polyethylene glycol compound, Carbowax 6000. The method is generally referred to as the Method of Tourtelot, who called attention to this geologically unknown technique in 1961, and it
is the method used for preservation of ball clay samples examined for this thesis. The average molecular weight of Carbowax 6000 is 6000 to 7500 and it melts at 60°C to 63°C. Its solubility percentage by weight in water at 20°C is 50. The cooled impregnated sample has a hardness comparable to that of talc.

The samples were taken from core samples. As it was impossible to guarantee sampling within minutes of a core emerging from the borehole, all samples were taken from the central part of the core, where moisture loss would be negligible, even after a day or more, which rarely elapsed in any case before samples were cut. Each sample was approximately one inch cube. The moist samples were then placed in a deep tray containing molten wax at a temperature of about 60°C. The Carbowax, being easily soluble in water, moved into the samples by diffusion. This was recommended to be left for three days at a temperature of 60°C; in practice, a longer time of five to seven days was found to be desirable, probably due to the minute pore spaces of the ball clays. Even then, the centres of the cubes were often not completely diffused by Carbowax and colour banding parallel to the sides of the cube was apparent, generally with the centre very much lighter in colour. The sample tray was then taken from the oven and the samples removed from the molten wax and allowed to cool. The cooled sample could then be sawn and ground to a thin section in the normal way, except that water could not be used as the coolant. Kerosene was used, as had been used by both Mitchell and Tourtelot. Also, because a technique involving heat could not be used due to remelting of the Carbowax, the slices and cover slips were mounted using Araldite AY103 Resin and HY951 Hardener. Final grinding proved to be a little difficult as the 'softness' of the material tended to allow the slice to be ripped by the carborundum powder. It was necessary to use a very fluid slurry of kerosene and carborundum powder and a much lighter pressure than normal for hard rock thin sectioning.
during grinding to obviate the imbedding of the abrasive material in the impregnated clay. Where quartz grains were part of the fabric, the slice could rarely be uniformly ground down to normal quartz birefringence colours of grey and cream, due to individual grains being torn from the matrix. Because of the softness of the impregnated sample, it was not possible to make the slices too thin although 40 microns was fairly easily achieved.

The effects of water replacement by wax on the clay were considered to be negligible by Mitchell (1956) as he did not observe any volume changes. He considered that his thin sections gave an accurate picture of the clay fabrics. The main disadvantage of Carbowax is that it is not isotropic and, according to Tourtelot (1961), the birefringence varies from slide to slide, giving second order yellow and red interference colours in most slides. The variations could well be due to the slight differences in water content of the original samples. The wax crystallises in feathery aggregates which fill any cavities or cracks in the natural material. Any such structures are readily picked out by the high order interference colours of the feathery aggregates filling them.

4.8. Since individual clay particles are submicroscopic in size, the optical properties of a randomly oriented group of particles are indeterminate. Such a group of particles appears uniform in colour when rotated in plane polarised light. If, however, the particles are aligned parallel to each other, they behave optically as one large particle and have definite optical properties. It was for precisely this reason that Mitchell (1956) developed the technique of impregnation with Carbowax. The early investigation of particle size seemed to indicate that the ball clays were sedimented in a flocculated state. As already discussed (Schofield & Samson, 1954), flocculation occurs with attraction on an edge to face orientation, which would be classed as random orientation.
Early inspection of thin slices confirmed this fact as there appeared to be no change of lighting as the stage of the microscope was revolved. As this evidence was rather negative, a dispersed sample was prepared. The initial problem was to achieve settlement of a dispersed sample, when even a very concentrated suspension does not produce a significant sedimented layer in a matter of weeks. In order to produce a solid from a dispersed solution, evaporation was resorted to. A suspension was prepared at 8% solids, and half the sample was deflocculated with 4% 1:1 sodium hydroxide/Calgon. Both samples were then dewatered to a plastic state by pouring the slurries into small plaster bats and placing them in a drying oven. Unfortunately only thin layers could be produced in this way. The sedimented samples were then impregnated with Carbowax in the normal way. Many other authors, such as Weymouth & Williamson (1953), were interested in the structure produced by reworking of some description, but samples produced by sedimentation were not involved.

For plate-shaped particles, the refractive indices in the directions of the long (a) and (b) axes are approximately equal, but are significantly different from the refractive index in the direction of the short axis (c). If a group of oriented particles is viewed under polarised light, looking down the short axis, a uniform lighting of the field is seen as the sample is rotated about the short axis. If the group of particles is observed normal to the short axis, four stages of illumination and extinction are observed as the sample is rotated through 360 degrees. Therefore, when a clay sample is to be optically studied, it is necessary to prepare two thin sections normal to each other for observation. This was carried out on both deflocculated and undeflocculated samples and the optical properties observed.

4.6.9 Investigation of the commercial seams of ball clay has, since the late 1700's, been carried out by boring (Vincent, 1971). The
Company's boring records go back to 1860, although many of the early borehole positions have been lost. These early borehole logs were very subjective, depending on sensitive teeth to determine the sand content, and other visual lithological and colour variations of the cores for identification. Occasional pieces would have been fired to check for colour and specking but no other test work would have been carried out. As the clay was mined on a piecemeal basis, in that a square pit or shallow shaft would be sunk on the borehole position, no widespread correlation was required. As production increased and greater continuity was required, correlation techniques other than appearance became necessary. V. R. G. Ashcroft-Hawley originated a 'fingerprint' technique in the late 1950's, depending on the physical characteristics of the clay, such as modulus of rupture and firing characteristics and limited chemical data. D. Mitchell, with increasing techniques available, developed the system to provide a classification based upon the physical and chemical characteristics of the seam. This classification was modified and developed by the present author to take account of all the information available, to enable correlation and recognition of trends over large areas. Although most of the deep boreholes can be generally correlated, boreholes as deep as 600 feet and only 300 feet apart could not be correlated in detail without this classification system. In the areas where general correlation is possible, detailed seam correlation also relies on the 'fingerprint' system.

The system involves the Company in a great deal of expensive test work to provide the data but the information provided has allowed the development of a complete seam numbering system covering the whole of the eastern outcrop. The technique for correlation has been used as a matter of routine in the exploration of the Bovey Basin, which exploration is by no means complete as yet, and all the stratigraphic and
structural information contained in this thesis is based on this information, although in no case is the actual classification of any seam shown.
5. REVIEW OF WHAT IS KNOWN OF THE BOVEY TRACEY BASIN.

5.1. The earliest references to the Bovey Basin are all concerned with the lignite rather than the ball clay. Risdon's survey ("The Chorographical Description of the County of Devon" which was published in 1714 and reviewed by W. Chapple in 1785) was written between 1605 and 1630 and refers to the occurrence of a 'peculiar' kind of coal at Bovey Tracy, the working of which for use in limekilns had recently commenced. This peculiar coal refers to the lignite which is also described by J. Milles in a letter to the Earl of Macclesfield reported in Phil. Trans. Vol. 51 of 1760. Milles also states that the coal was discovered in 1745, but this statement is contradicted by Risdon writing over a century before this date. Brief accounts also concerned with the lignite are given by Kirwan (1784), Maton (1797), Hatchett (1797 and 1804) and Vancouver (1808).

The first significant reference to the ball clay is found in Polwhele's "History of Devonshire" (1797) where a letter is quoted from a Mr. Hill of Hennock (a village well known for metal mining some three miles to the north of the Bovey Basin, on the edge of the granite). The letter describes the occurrence of clay overlaid by coarse gravel at Kingsteignton, the deposit extending through Teigngrace to Knighton. The clays are classified as potter's clay and pipe clay (used in the manufacture of clay pipes). This is the first reference to a division of the clays, and one which Scott (1929) was to develop further, and which modern exploration has shown to have a stratigraphic basis. The 'potter's clay' is described by Mr. Hill as "pure white or pure black" and he remarks that it is the black variety which, when fired, gives the better colour. Mr. Hill draws attention to the general westerly dip of the beds and their association with beds of lignite or 'Bovey Coal' up to one foot in thickness. The clay was cut into ten-inch cubes, or
'balls', weighing 30-35 lbs each and taken by packhorse to Hackney Cellars, which were between Newton Abbot and Kingsteignton (the Hackney Canal has now been filled and the old buildings replaced or converted to house a Motor Body Company). The working of the deposit is said to have commenced about 1740, but probably was worked for limited local use, such as pipe making at Knighton, before that date. (There is a reference to 28 tons of tobacco pipe clay being sent from Exeter to London in January 1721 - Stretton, 1970). Certainly, by the end of the Eighteenth Century, exports through Teignmouth had risen to over 10,000 tons annually. A description of the beginnings of the ball clay trade is given by Bulley (1925).

5.2. The first mention of the deposits in the Nineteenth Century is in T. Brice, "A History and Description of the City of Exeter" (1802), in which the extension of the clay deposits from Heathfield through Teigngrace and Newton Abbot Marshes to Aller is noted. Brice also comments on the high temperature of the 'mundic water' which comes out of the clay beds (mundic water is water containing hydrogen sulphide and iron salts). McCulloch (1814) and many geologists since (because of the unique character of the Bovey Basin) have been attracted to the deposit although mainly to the lignite and the associated plant remains. The first suggestion traced regarding the source of the material is contained in Lysons' "Magna Britannia" (1822). This gives the probable source of the clays and gravels as Dartmoor. In the same work it is stated that the clays were first worked about 1730, agreeing very well with the date suggested by Polwhele (1797), and that the annual export through Teignmouth had risen to 20,000 tons by 1820. There is also the first mention of boring, in the Parish of Ilsington, where the most surprising fact is the depth to which penetration occurred. E. W. Brayley in Moore's "History of Devonshire" (1829) and W. Turton & S. F. Kingston, "Guide to Teignmouth" (ca. 1832) give general descriptions of five distinct
beds of clay, the eastern one being the widest and consisting of pipe clay, often impregnated with iron and associated with sand (probably the 'stoneware' clays of Scott which are recognised now as the Abbrook Member). The two middle beds are composed of black clays and the two western ones of 'cracking' clay. These latter clays are probably at the bottom and top of the Southacre Member and conform to Scott's 'whiteware' clays. It is also stated that the clay on the right (western ?) bank of the River Teign is inferior to that on the left bank. Brayley also supposes the clays to have originated in a lake with its exit towards Torbay.

5.3. In 1839 De la Beche published the "Report on the Geology of Devon, Cornwall and West Somerset", which contained a section referring to the 'Supracretaceous' or Tertiary Deposits. De la Beche says "the clays, sands and lignites, deposited in the Bovey depression on the west of the Haldons, are the only beds of any importance which have yet been observed above these lower flint and chert gravels. Upon the undisturbed green sand of this depression we find a gravel of chalk flints and chert resembling the lower gravels above noticed, particularly those on the Haldons being like them slightly rounded. Upon these the clays and sands of the Bovey deposit may be seen to rest, and there can be no doubt that the flints and cherts were reduced to the condition in which we find them before the Bovey beds were formed". It is not clear whether the flint and chert deposits to which De la Beche refers are representative of basal Bovey deposits or are, in actual fact, heading deposits, as such confusion still exists. 'Head' can be readily recognised in the working areas but, towards the margins, the distinction becomes obscure. De la Beche continues with a discussion of the Haldon clay which he concludes "might be a resettlement of the Bovey clay". He then says "with the exception of a thick bed of lignite, which occurs near the Pottery on the south of Bovey Tracey,
the lignite of Aller Mills, and portions of the same substance sometimes mixed with the clay in various parts of the deposit, organic remains have not hitherto been detected in it. We are therefore deprived of any aid which animal exuviae might have afforded us in referring the Bovey clays and sands to any particular geological date". Although the lignites are now known to exist over far greater areas and levels than ever envisaged by De la Beche, his comment on the absence of animal fossils is unfortunately true. All efforts since 1839 to age the Bovey Beds have had to be of necessity confined to plant remains which are in the main very long ranging and therefore not good indicators of age. De la Beche, on the flimsiest of inferences, supposes the age to be "towards the later part of the Supracretaceous period".

He continues "From the manner in which the Bovey deposit conforms to the valleys adjoining it, the character of the clays and sands, and the greater purity of the clays towards Kingsteignton and away from the granite of Dartmoor, we may be led to infer that, prior to the production of the Bovey Beds, a depression was formed in this locality, subsequently to the destruction of the mass of chalk and a considerable portion of the green sand which there once existed, and that the materials for this deposit were chiefly derived from decomposed parts of the adjoining granite gradually carried down by streams, the quartzoze parts forming the sands, and being sooner brought to rest than the decomposed felspar, which was borne onwards until it could quietly settle, in the same manner that similar china-clay is now artificially prepared in the south part of Dartmoor, and in Cornwall, by turning streams of water upon decomposed granite". The last sentence would provide a useful source of china clay but, unfortunately, the granite needs to be 'kaolinised' hydrothermally and not merely decomposed in order to produce china clay economically. China clay is also very much coarser than the ball clays and sedimentation of china clay is comparatively rapid. Nevertheless, De la Beche formalises the concept
of a Dartmoor provenance for the ball clays, a concept which is still the most likely.

De la Beche, whilst discussing the absence of animal fossils, supposed "the depression to have formed a freshwater lake bounded by dry land". De la Beche as early as 1839 hypothesised not only a Dartmoor provenance but also a lacustrine sedimentary environment. Croker (1856) describes the Bovey Basin, confining himself mainly to the Bovey Lignite Pit area and Bovey Heath, and describes a dip of "11 inches in the fathom" (1 in 6½) to the south-east. The author also referred to "the extensive denudation that the district had undergone" and pointed to "the Dartmoor granite tract as the source of the clays of the lignitic deposits".

5.4. Key (1861) described the Bovey Deposit, in the longest paper so far written on the area, with a far greater emphasis on the clays than is found in any previous writings. He obviously had considerable experience of working in the deposit, as he says "Having been for the last ten years engaged in working and boring the various beds of clay, I may have become possessed of facts not generally known to geologists, bearing on the origin and nature of the deposit, and which may assist in some degree to fix its relative age". It is significant that the present author's experience is virtually identical (having joined the clay industry in 1964) and that the aims of this thesis are in many ways similar.

Key draws attention to the whole basin being "filled up with loose material, consisting of various kinds of clay, silt, sand, lignite and gravel, deposited in beds with considerable regularity. At one place it has been bored to a depth of 200 feet, and in many places to 130 to 150 feet, without meeting rock". He describes the strata as commencing on Knighton Heath and running down the eastern side of the
basin, and mentions three parallel beds of clay, the eastern or pipe clay (the white body) and two western beds of potters' clay (the black body), resting on, separated and covered by other parallel beds of muddy clay, silt, sand and gravel, all having a westerly dip.

South of Newton Abbot Railway Station the beds of fine clay thin out to a mere trace but occur again as a well-defined and regular deposit at Decoy but, here, the dip is changed from the west to the east, the pipe clay now being found to the west and the potters' clay, accompanied by seams of lignite, to the east. Further south, the beds of fine clay thin out again, still with easterly dip, becoming well-defined again at Aller, especially the potters' clay and lignite (the pipe clay becoming sandier and stained). Key also states that traces are found as far south as "the Atmospheric Engine-House, above the Torr Railway Station".

The information regarding Decoy and Aller is of some importance as very little information is now available since the last working in this area (Decoy Main Quarry) closed in 1967 because of the proximity of residential development.

The western outcrop is mentioned but dismissed as "the clay found by boring being, for the most part, unsuitable for commerce; it is highly stained with red matter, and gravelly". The dip is described as to the east.

Key's statement that "the whole is covered by a deep "head" of gravel, such as would be washed from disintegrated granite" must have referred to the Bovey Pottery area, as much of the rest of the head contains flints. He also published sections (taken by Croker in 1841) of the Bovey Pottery area from which he concludes "The order of deposition observed in this section corresponds with what would be expected to result were a river, bringing various kinds of sediment, to discharge itself into
a deep lake. Three further sections, at New Cross, Decoy and Aller, are also drawn. He mentions "several seams of lignite, almost perpendicular in dip for the first 15 to 18 feet from the surface." This latter phenomenon was undoubtedly due to cryoturbation. Key states, referring to a non-published paper, "it will be seen that the clay is continuously deposited in the valley leading to Torquay; therefore, if a lake once existed, in order to deposit the clay, the current must have run in the direction of Kingskerswell and Torquay, and did not, as now, find an exit to the sea by way of Teignmouth." He develops this argument at length, supposing a lake extending from Bovey Tracey to Torre, and puts forward seven statements as conclusive evidence for this lake. These statements are as follows:

(1) That the Bovey deposit is composed of various beds almost identical with the components part of the granite.

(2) That the strata run, for the most part, parallel with an extended outline of the marginal hills, and dip from the sides towards the centre of the basin - the nearer the centre, the greater being the dip (this latter proposition is now known to be essentially incorrect, and the former proposition does not apply to all margins).

(3) That the finer material is deposited towards the sides and coarser towards the centre (again not wholly correct).

(4) That, where the basin contracts in width, the finer beds contract in thickness, and sometimes disappear; on the contrary, where the basin widens, the purest and most regular beds of clay are found.
(5) That the northern part of the deposit is at first irregular, and composed of coarser substances than the central and lower portions (this point will be elaborated and expanded further in this thesis).

(6) That, on the eastern side of the basin, the beds of fine material are more developed than on the western side (this is undoubtedly so, but hardly substantiates the argument).

(7) That the various beds run in the direction of, and seem to point to, the River Bovey as the source from whence they were derived.

Key considered the lake to have been elongate, but contracted in the middle, fed by a rapid river entering the lake at its upper end and having its tributaries in granite hills clothed with forest trees, these tributaries carrying clay derived from decomposed felspar, earthy matter from the vegetable mould, siliceous sand and gravel, vegetable matter and stones and boulders of various kinds. Key describes polished stones in the clays. These stones have not been found in modern times except in the first ten feet where the stones were probably derived during deposition of the 'head' under perma-frost conditions. Key also assumes that the 'head' was laid down by the delta immediately after filling of the lake - a mistaken hypothesis, later disproved by Pengelley (1862).

5.5. Soon after publication of Key's paper in 1861, another very significant paper was published in 1862. This was the work of Pengelley & Heer, under the patronage of Miss Burdett Coutts. Except for a brief comment regarding the Dartmoor origin of the clays and sand, Pengelley devotes most of his attention to a description of the Bovey "Coal Pit".
including a detailed section through some 125 feet of strata including 72 beds of lignite and clay, with some sand and sandy clay at the top. The dip of these beds was 12° towards S35°W (magnetic). The top bed was in fact the 'head' and Pengelley confirms that no stones are found below this level, in contradiction to Key. Pengelley also noticed that the clay is not generally characterised by lamination when first dug. Because of the flat pieces of lignite, known as 'board coal', Pengelley infers that "as pressure must be regarded as essential to this flatness - much of the superior portion of the deposit has been removed by denudation". He also states that the 'head' is unconformable on the underlying lignites and clays with probably a great "chronological interval" between the two deposits. Heer assigns the dicotyledonous leaves found in the 'head' to a colder climate than Devonshire has today. Pengelley, for the first time, mentions faults within the basin, a fact denied by Key only a year previously.

All the plant fossils collected were submitted to Dr. Heer, Professor of Botany at Zurich, who determined 50 species of plants and one insect from the true Bovey beds and four species of plant from the overlying 'head'. Of the fifty species, twenty-six were new species, nineteen were known from the Miocene of Continental Europe, and five were of doubtful determination. Plants identified included Sequoia couttsiae, the ferns Pecopteris lignitum and Lasrae stiriaca, large numbers of small seed-vessels identified as Carpolithes nitens, the seeds of three species of Nyssa and two of Anona and the water lily, Nymphaea. Pengelley says "following subdivisions of the Miocene beds adopted by leading geologists on the Continent, it appears that of the (nineteen) previously known species fourteen occur in the Tongrian, or lower stage, seventeen in the Aquitanian, twelve in the Mayencian, five in the Helvetian and eight in the Oeningian or highest". He later continues "that of the two not known to occur in the Aquitanian stage,
one is apparently confined to the Tongrian below, whilst the other has
been met with in this and also in the Mayencian above (but only in a
single locality in each) and may, therefore, be looked for, sooner or
later, in the Aquitanian also”. On this somewhat flimsy evidence, an
Aquitanian or Lower Miocene age was accorded to the Bovey Deposit by
Pengelley.

Pengelley concludes that the palaeogeography of the area in
Miocene times was very similar to the relief of today. "The Teign and
Bovey rivers were then in existence, but, instead of the latter being
tributary to the former, their mouths were three miles apart, and both
fell into the same deep, sluggish, freshwater lake, which occupied the
site of the present Bovey plain, and was guarded by Dartmoor and the
other hills which still constitute the prominent characteristics of the
district".

In 1865, Pengelley published a further paper on the "Correlation
of the Lignite Formation of Bovey Tracey, Devonshire with the Hempstead
Beds of the Isle of Wight". On fairly slender evidence, he correlates
the Bovey Beds with the Hamstead Beds, which were considered at that time
to be Miocene in age. The Hamstead Beds are now included in the Middle
Oligocene so Pengelley unwittingly was the first to give the Bovey Beds
an Oligocene age.

5.6. The papers by Key (1861) and Pengelley (1862 and 1865) were
the most significant works produced to that time and probably for a long
time afterwards. Until 1867, geologists were virtually unanimous that
the source of the ball clays was Dartmoor. However, Maw (1867)
introduced the idea that perhaps Dartmoor was not necessarily the source
of the material. More than a century later, conclusive proof for either
a Dartmoor source or any other provenance for the kaolinites found in the
Bovey Basin has not materialised.
Maw (1867) considered the white clay to be derived by dissolution of the calcareous portion of the chalk. He says "Many of the Tertiary white clays of Devonshire and Dorsetshire are chemically pure silicate of alumina or impalpable silica, and it seems impossible to account for their accumulation, almost entirely free from admixture, as the result of the mere mechanical degradation of previously existing beds. However effective the separating power of water may be in sorting and dividing coarse from fine matter, its mechanical operation could not isolate silicate of alumina from other materials of similar specific gravity". Maw also draws attention to the fineness of the ball clays, "an impalpable condition which distinguishes them from nearly all other argillaceous deposits". He continues "In testing the state of division of the Bovey Tracey and Wareham clays, I found that after mixing them with water to the consistency of cream, and passing them through a fine silk lawn containing 10,000 perforations to the square inch (100's mesh or 150 microns) no appreciable quantities of coarse matter remained behind from most of the samples, not even to the weight of a grain out of several pounds of clay. I can state from the results of a number of experiments on clays and marls of various ages and formations, that such a state of subdivision is peculiar to these Tertiary clays". The result of these experiments is hardly surprising when most of the ball clays are 95% finer than .20 microns.

Maw devotes much of his paper to a vain attempt to prove derivation of the ball clays from the chalk from chemical analysis. The only interest to present-day readers is in the provision of information by Mr. Charles D. Blake of Watts, Blake, Bearne & Company. It is interesting to note that the forerunner of the Company which was destined to become the largest ball clay producer a century later should, at that time, be providing information to geologists in a similar fashion to modern times. The basis of chemical analysis was obviously very
different than today and completely inaccurate (e.g. China Ball Clay is quoted as containing 67.5% silicate, whereas its true silica content is in the order of 45%). Mr. Blake quotes silica varying from 50% to 95% and alumina from 4% to 50%. The production of a 95% silica clay or a 50% alumina clay would certainly cause problems in quality control in 1974. Because of the obvious inaccuracy, most of Maw's argument is invalidated, although the principle not necessarily so.

Maw continues by referring to Pengelley & Heer (1862) and their proposition that the probable derivation of the deposit was from the degradation of the Dartmoor Granite. "This inference seems to be due more to the geographical proximity of the granite to the clays of the lignite-formation than to any more certain evidence". This inference is still one of the few pieces of positive evidence available at the present time. Maw also considered the deposit to have covered a far greater area than its present confines, and he also noted the fact that it was intersected by considerable faults.

Although Maw's contribution has little of substance to add to the knowledge of the Bovey Basin, he nevertheless introduces an element of doubt into the hitherto unanimous complacency exhibited by geologists when referring to the provenance of the Bovey Basin.

Pengelley replies to Maw in the British Association Transactions for 1870, giving five reasons for the derivation of the clay from Dartmoor. The most significant arguments he puts forward are concerned, firstly, with the beds of sand, which he suggests are little more than disintegrated granite, being made up of unrounded quartz, quite angular felspar and grains of schorl and, secondly, with the unmistakably granitic origin of the sand in the clays.
5.7. Mackintosh, in the same year (1867) as Maw published his paper, published some equally wild hypotheses as regards the nature of the deposit. 1867 was not a particularly good year for substantiated theories regarding the Bovey Basin. Mackintosh writing about the Bovey Basin in the "Railway Geology of Devon" says "The railway sections between Newton and Bovey seldom or ever penetrate beneath the 'head' into the body of the formation but the coalpit can be soon reached from the Bovey Station". This lack of evidence does not deter him and he then continues to try to show that the Bovey Beds originated in a marine or fluvio-marine environment. He dismisses the occurrence of freshwater seeds as having drifted into a saltwater estuary or creek from a freshwater habitat. Yet his own evidence is so flimsy and circumstantial that it warrants no further attention.

Pengelley produced two papers, one in 1875 and the second in 1883, regarding the 1866 finds in the heading at Zitherixon (a pit belonging to Watts, Blake, Bearne & Company). These finds, now part of a WBB collection, were later identified as Bronze Age, a date which has some significance in investigation of the 'head' deposits (Gouldstone - Personal Communication, 1973). These two papers contain very little new information regarding the Bovey Beds, except the statement in the 1883 paper that "it has been somewhat recently stated that the Bovey Tracey Lignites, instead of being Miocene are of Eocene age". This latter statement was referring to a work published by Gardner in 1879 on the "Correlation of the Bournemouth Marine Series" in which he (Gardner) doubted the Lower Miocene age of the Bovey Beds and identified them with the Middle Bagshot deposits of Bournemouth. Gardner says "The fossil plant remains met with in the Bournemouth Beds, especially those in the marine series, are so strikingly similar to the Bovey Tracey fossils as to make it clear to my mind that the latter have been wrongly assigned to the Miocene. I believe, in fact, that they are simply an outlier of the Bournemouth Series, from which they are but eighty miles distant."
Whether we compare the ferns, as Osmunda (Pecopteris) lignita, Lastræa bunburyi, the Cactus (Palmacites daemonorops), the fruits, conifers or dicotyledons, it is seen that by far the larger proportion are not only specifically identical, but occur exactly in the same combination and manner of preservation. The synchrony of the Bovey with the Hempstead Beds has been inferred on the most slender grounds and scarcely deserves attention now that it is opposed by strong evidence pointing in another direction. Scott (1929) attributes "a connection between the lake in which the Bovey Beds were deposited and the Eocene River which gave rise to the Bournemouth Beds" to Gardner. The present author could find no such reference in Gardner's 1879 paper.

The Nineteenth Century closes with a paper by Reid (1898) on the Eocene deposits of Devon in which he says "With regard to the age of the pipeclay and lignite of Bovey, it is difficult yet to speak with confidence. Mr. Starkie Gardner has pointed out that the flora is probably of Bagshot age, not Miocene as stated by Heer, and the resemblance of the deposits and their flora to the undoubted Bagshot of Dorset is most striking. Still one cannot yet say that the botanical evidence is conclusive, for the species are few and greatly need reexamination. Other fossils are almost entirely absent".

Thus, the turn of the century occurred with two major questions as yet not satisfactorily answered:

(a) the origin of the ball clays

and (b) the specific age of the Bovey Beds.

The extremely fine nature of the ball clays was not then realised, so a third major question

(c) how does sedimentation of such fine particles occur?

has not been considered.
5.8. The first paper of note in the Twentieth Century was published in 1909 by Jukes-Brown and was entitled "The Depth and Succession of the Bovey Deposits". He commences by describing a borehole made by Messrs. Candy & Company at Heathfield (this Company still produces tiles at Heathfield), first reported by Mr. H. B. Woodward on a Geologists' Association excursion in 1900. This borehole had been bored to a depth of 456½ feet in the bottom of a 70-foot pit, thus covering some 506½ feet of Bovey Beds (allowing for 20 feet of heading).

The information from this borehole, the deepest in the Basin to that date, was summarised as follows:

| FEET |
|------------------|------------------|
| Superficial deposits, gravel and sand. | 20 |
| Clay with some beds of sand and one of lignite. | 50 |
| Beds of clay and sand, with four of lignite. | 100 |
| Beds of clay and sand, with one of lignite. | 100 |
| Beds of lignite and clay, with a thin bed of sand at 300 feet | 36 |
| Beds of lignite divided by layers of brown clay | 220½ |
| | 526½ |

The more detailed logs published by Reid (1913), Strahan (1920) and Scott (1929) all disagree with Jukes-Brown's summary, apparently reaching a depth of 456 feet, including 56 feet of pit.

Mr. Woodward stated that the dip seen in the open pit was 80° to the WSW. Jukes-Brown's first comment of note concerns the basal gravels or marginal beds, which he says "do not extend all round the basin, but are principally found on its eastern and south-eastern sides. On the eastern side, from Kingsteignton northwards to Bellamarsh, there is a nearly continuous border of sand and gravel which appears to pass westward under the clay and lignites which have been so extensively worked near Abbrook, Preston and Kingsteignton ....... while round the western half of the main basin, i.e. that part which lies to the west of the River Teign,
the basement beds consist of sand, though in places (as at Staple Hill) there are pebbles and blocks of chert in the sand". He continues with a discussion of Pengelley's work and attempts some tentative correlation of the lignite in the Heathfield borehole with the "coal pit" section. His most significant comment is "Here I think we may well ask whether the highest sands and clays and even the highest lignite and clay of Heathfield, are of the same age as the lignitic series which lies several hundred feet below them". He suggests that the question may be answered by Clement Reid in 1910. Based on this evidence, he constructs a remarkable section through the basin which, considering the quality of the information, presents a perceptive picture of the Bovey Basin.

Jukes-Brown now goes on to suggest an idea which had hitherto apparently been overlooked but which is fundamental to most authors writing after that date. Until 1909, it had been generally supposed that the Bovey Basin was a natural lake-basin, and that its present limits were not far removed from the original lacustrine area. Jukes-Brown had little doubt that the Basin was tectonic in origin and "not in any sense an actual lake-basin". He supports this statement by arguing: "if the Bovey Basin had been part of a lake, fed by one or more copious rivers, and if the lignites had been formed by masses of driftwood carried down by these streams, during periodical floods, one would have expected the resulting deposits to be an alternating series of sands, clays and lignites throughout the whole thickness, or possibly an upward transition from gravel and sand through sands and clays to clays and lignites, and finally to the peat and lignite of a silted-up swamp. Instead of this being the case, we have the lignites in the lower part and the alternating series of sand and clay in the higher part".

Jukes-Brown naturally follows to an equally fundamental problem - that of the occurrence of the massive seams of lignite. He firstly discusses Heer's (1862) analysis concluding "Heer supposed the
only alternative to be either the transport of driftwood into an open lake or the growth of moss in a peat-bog, but there is a third and much more probable method of accumulation, and that is the growth of a forest swamp, like the Great Dismal Swamp of Virginia. After further discussion of Heer's work, he further concludes "that evidence afforded by the plants is, therefore, strongly in favour that the flora of the beds containing their remains is a swamp flora, and consequently that these lower lignite beds have been formed where they are now found by the growth and decay of the plants which occur in them". He comments that the absence of mosses in the lignites could be explained by the fact that, south of a certain line of latitude in the United States, peat-forming mosses do not flourish, and that they do not occur in the great swamps of Virginia and Carolina. He mentions that it is the Great Dismal Swamp that should be looked at for a modern counterpart of the conditions under which the lignites were formed. A description is then given of the Great Dismal Swamp from Lyell's "Principles of Geology".

He then gives the history of the district of the Bovey Basin as he sees it. During the Lower Eocene, the West of England was a land surface, and eastern Devonshire was covered by a sloping table of chalk which was being reduced to the condition of a peneplain by subaerial detrition. After Bagshot times, the South of England seems to have sunk slowly and continuously, allowing the shallow-water Bournemouth Beds to spread further and further westward leading to the formation of lagoons, lakes and swamps on the low-lying plains adjoining the rivers which emptied into this bay. The Bovey Basin would be part of this lake-and-swamp area. The Dartmoor Granite was exposed, but with less relief than today, and there was probably higher ground to the south. Jukes-Brown supposed these conditions to be similar to those which led to the formation of the Great Dismal Swamp and that continuous subsidence resulted in the accumulation of much thicker masses of lignitic materials. For a long time it would seem that the vegetation was so luxuriant that, in spite of
the subsidence, the Heathfield swamp was always choked with the decaying vegetable matter which has since consolidated into the lignite beds. His next statement is rather odd: he says "There came a time, however, when the swamp was invaded by the waters of an adjoining lake and the forest was buried under a deposit of lacustrine mud, such invasions became frequent until at length it was only occasionally that the swamp vegetation could once more establish itself over the same tract of ground". It is strange that the erudite Jukes-Brown did not suppose that a lake was established by the accelerated but similar tectonic subsidence which powered the swamp environment rather than by the invasion from a conveniently-placed existing lake. He also does not realise that the adjoining lake would have given rise to contemporary lacustrine deposits, a point which will be discussed further in this thesis.

Finally, Jukes-Brown concludes that lacustrine conditions were permanently established, giving rise to the white clays and fine yellow sands, derived from Dartmoor.

Sedimentologically, this paper was very significant. Jukes-Brown suggested:

(a) tectonic control of the sedimentation of the Bovey Basin

and (b) that the environment changed with time to yield differing sediments.

He also made a brave attempt to explain the large masses of lignite and to explain the sedimentation of the sandier section. He makes no attempt to discuss the full implications of the tectonic basis nor that different environments producing dissimilar sediments could occur at the same time in adjacent areas.
5.9. As promised by Jukes-Brown (1909), Reid and his wife published the results of their collecting in 1910. They start by clarifying Heer's work and pointing out that the Hamstead Beds (a change of spelling from the "Hemstead" of Pengelley) are now known to be Middle Oligocene, and not part of the Aquitanian, and continue by commenting that Gardner made no collections at Bovey and that, in his Bournemouth collections (now in the Museum of Natural History), they could find nothing to justify the Bovey Beds being identical to the Eocene Bournemouth Beds. The Reids claim the flora to be almost identical with the Wetterau lignites (in the Rhine Valley, Germany) of supposed Upper Oligocene age, continuing "As the Rhine lignites occur in latitude almost identical with that of Bovey, and the physical conditions and surroundings were very similar, we should expect to find the contemporaneous floras almost identical except for endemic species". They also suggest that the Bovey flora shows a gradual dying out of the tropical or warm temperature plants and the incoming of a few northern genera. With the good auspices of Messrs. Candy & Company, the Geological Survey obtained portions of the borehole described by Woodward (1900) and Jukes-Brown (1909) and also some samples from the 'coal-pit' which was by now overgrown and flooded. The plant remains were extracted by the Reids by boiling down the carbonaceous clays with soda. They considered the beds near the surface at Bovey to be the same as those found at depth at Heathfield. The boiling with soda produced numerous unrecorded species, "some of them new and some already known from the Wetterau lignites and, although there is a considerable endemic element in the Bovey flora, all the geological evidence suggests that we are dealing with a Continental area, not with an island". This flora suggested to the Reids "a dense jungle with many climbers, surrounding and overhanging the lake, the shores of which plunged so steeply that there was little room for either marsh plants or for rooted aquatic forms". The remainder of the paper is devoted to a description of the plants not described already by Heer.
Reid contributed the description of the Oligocene in Ussher's Memoir on "The Geology of the Country around Newton Abbot" (1913). This contains little that is new but is mainly descriptive of the Bovey Basin and of the work that had already been done. He says "The Bovey Basin appears to be a deep rock basin originating in a 'rift valley', the middle of which has locally sagged far below the level of the outlet". He compares the trends of the area to the folding of the Hampshire Basin, despite the differences in direction, and infers a similar filling with Upper Oligocene strata.

Reid also suggests that the 'lake basin' was about 1000 feet deep, with torrents pushing extensive deltas of granitic sand and mud, mixed with masses of wood brought down from the ravines above. He obviously did not think much of Jukes-Brown's ideas on the deposition of the lignite. Reid continues "the finer clay, obtained from the decomposed felspar of the granite, travelled further, and was at length deposited in the still water towards the south-east end of the lake, where it now forms thick beds of pottery clay". It is remarkable how perceptive this older generation of geologists were, although no realisation has come yet regarding the difficulties of sedimenting ball clays. Reid concludes this pertinent paragraph with "other materials, washed in from the steep sides of the lake, included chalk-flints, Greensand chert, and stones from the Permian and Culm Measures, but the mass of the deposit consists essentially of material derived from Dartmoor, then perhaps several hundred feet higher, which dominated the lake on the north and west". Whilst not disagreeing with the last part of this quotation, the present author has not, in nearly ten years spent in the clay industry, seen any stones, cobbles or pebbles of the materials described in any pits, mines or boreholes (which reach over 1000 feet in depth and cover a wide area in the basin), other than in the 'head' which is Pleistocene or more recent in origin. It is probable that such material
is found in the basal parts of the basin but this is outside the author's experience. Reid later in his description confirms this by saying "the deposits consist of beds of sand and pottery clay, mainly derived from the granitic moors, alternating with seams or masses of brown coal or lignite. The marginal, and apparently the basal, deposits are coarsely sandy or even gravelly and contain a considerable admixture of other rocks such as chalk-flint and Greensand cherts".

Reid again talks of very high dips, which he tries to explain by compression of the vegetable matter to form lignite, whilst in fact these high dips are not observed today, except near the surface due to cryoturbation.

Reid mistakenly attributes the origin of the basin to transverse folding and sinking in comparatively soft strata which now strike across the valley further south. This is contradicting his earlier reference to a 'rift valley'. He then gives a graphic description of the sedimentary environment, with a warm rainy climate, with abundant forest trees and climbers in the upper reaches of the valley, a lake "turbid with white clay" from constant floods, so that even the coarse sandy deltas are usually mixed with clay and the lignite is full of seams of it. Few aquatic plants and little animal life would flourish in this turbid water. Reid concludes a paragraph describing the vegetation with the statement "the parts of the deposit examined by the Survey showed a sharp distinction between well-preserved vegetation and a matrix containing thoroughly decayed humus which accompanied it; we could find little or nothing suggestive of a swamp-deposit and gradual decay in place".

In 1920, Vol. VII of the "Special Reports on the Mineral Resources of Great Britain" was published. The volume edited by Sir A. Strahan included a chapter on lignites and, in particular, a section on the Bovey lignites. This section gives information
regarding the analysis of lignite and is only really notable for repeating Penglley's "Coalpit" section and the Heathfield borehole, together with details of four more recent boreholes sunk by a German company, details of the Teigngrace borehole sunk to 667 feet in 1917-18, and descriptions of several working shafts in various localities.

Scott (1929) in "Ball Clays", a Geological Survey publication, summarised and gathered together all the information so far reviewed in this chapter. The various borehole logs are repeated, with some additional shaft information. The only significant addition to the interpretations is that in the Heathfield boring (presumably Scott is referring to the lower part of Bovey No. 4 Borehole) the hard material encountered is termed "granite" but (Scott says) it is probable that it was "sand rock". With this statement the present author would certainly agree. Sandrock is a siderite cemented sandstone and is the only "hard rock" material encountered in the main Bovey sequence, and it is not uncommon.

He produces a sketch map (reproduced in FIG. 5.1.) showing the outcrop positions of the ball clays. He divides the clays into the whiteware and stoneware clays, and indicates their outcrop positions and dip but, basically, does not produce any further information regarding their age, provenance or sedimentology. In a later chapter of the publication, Chapter 6, he discusses the mineralogy and chemistry of the clays, much of which was new at that time. He says "As might be expected from the mode of origin of the clays, the minerals of the acid igneous rocks are common, especially in the beds of siliceous clay and sand. Among these may be mentioned quartz, felspars, micas, hydromicas, chlorites, rutile (footnote - possibly authigenic), zircon, magnesite, ilmenite and tourmaline, all of which can be identified in the heavy residues obtained by washing the Bovey and Poole deposits". Naturally, quartz is most common. Scott also mentions the authigenic oxides and
FIG 5.1. Sketch Map reproduced from Scott (1929) showing the outcrops of Ball and Stoneware Clays.
sulphide of iron. The presence of kaolinite was confirmed by thermal analysis and, for the first time, there is recognition of the "colloid particles" in the ball clays. Analyses of ball clays are also given and, although their accuracy is much better than any previously quoted, they have limited use when compared to modern chemical analyses. One fact quoted has subsequently been independently verified by the present author. This is that the titanium dioxide content of the ball clays increases with the proportion of silica. Scott also identified mundic as the marcasite type of pyrite. Much of his work is concerned with the ceramic properties of the ball clays, which he describes in some detail, thus making the publication particularly valuable to the ceramic industry and the clay producers in general.

Scott's connection with the ceramic industry is demonstrated by a paper read to the Ceramic Society in 1929 before the publication of "Ball Clays". This paper is very similar in introduction and content, except that the borehole logs are not quoted in full. The paper however includes a pertinent section which is not included in "Ball Clays". Scott says "In order to explain the origin of the deposit, it is necessary to consider the changes which occurred in this part of the world prior to the deposition of the Bovey beds. At the end of Cretaceous times an uplift occurred in the west of England, and continued throughout the Eocene period, so that with the rise of the land to the westward, the sea margin gradually retired eastward. The general drainage lines in Eocene times seem to have been easterly and it is probable that the materials of the Dorset ball clay deposits were brought from Dartmoor by such an eastward flowing river. During the Oligocene period this uplift continued, and was accompanied by further eastward recession of the sea. After Middle Oligocene a rift valley with a north-west and south-east trend developed across the western margin of Dartmoor. This direction coincides with that of many of the Tertiary faults in
south-west England. It is difficult to determine how far this rift valley extended to the north-west but the distance may have been considerable, as there is a fair alignment between the direction of the Bovey valley from Newton Abbot to Chagford, and that of the similar depression in which the North Devon ball clay deposits occur. This is the first reference traced to the connection of both the Bovey and North Devon deposits to the same fault system, which we now know as the Sticklepath Fault.

Scott also recognises that granites are kaolinised by pneumatolytic action and goes on to say "The granite to the north-west of Bovey Tracey has been highly kaolinised.....". This unfortunately is a figment of his imagination, as the nearest hydrothermal china clay deposits are some twenty miles to the west-south-west.

For some reason, Scott mis-spells Tracey, with the 'e', throughout his paper delivered to the Ceramic Society, yet it is correctly spelt in "Ball Clays".

5.10. The next twenty-seven years produced little of note to add to the knowledge of the Bovey Tracey Basin. In 1957, however, two papers were published which clarified two major questions:

(a) the mechanism which caused the Bovey Basin

and (b) the age of the beds which filled the Basin.

Blyth produced a paper on "The Lustleigh Fault in North-East Dartmoor". He correlates the Lustleigh Fault with the Sticklepath Fault of Dearman (1950), and he suggests a right-handed tear movement. Regarding the relevance of the fault system to the Bovey Beds, Blyth says "When the Lustleigh-Sticklepath fault system is viewed in relation to a wider area, it is evident that its continuation to the south-east, where it passes under the Oligocene deposits of the Bovey "basin", would lie
parallel to the long axis of that structure. Clement Reid (1913, p. 104) regarded the Bovey 'basin' as a 'rift valley', along which subsidence has taken place, thus allowing the accumulation of hundreds of feet of clays and lignites'. Blyth continues with some mistaken inferences regarding the clays to the east of Knowles Hill, and then continues the fault to the coast near Torquay. It is surprising to find that the generally accepted concept of the Sticklepath Fault system was not established until as late as 1957.

The other paper in 1957 was by Chandler, on "The Oligocene Flora of the Bovey Tracey Lake Basin, Devonshire". She says "The lignite deposit suggests an accumulation of plant débris much of which was swept from a steep warm valley into an isolated lake basin lying in Palaeozoic strata. The lake was surrounded by marshland and tree covered slopes which contributed to the fossil flora". Chandler also points out that "these lignitic beds differ from all other plant-bearing localities in the South of England Tertiary Beds in that they occur in isolation in a deep rock-basin formed of Palaeozoic strata, whilst other plant-bearing beds can be dated within certain limits from marine strata with which they are often interbedded".

Chandler reviews the work of Heer and Reid and adds some new genera but, basically, with the rich abundance of Sequoia, Calamus and the fern, Osmunda, concludes that rarer species are represented only by one or a few individuals which she says may well be because dense Sequoia forests and Calamus jungle do not provide a congenial habitat for a wide range of plants.

Chandler, in discussing the age of the beds, discusses the ranges of various species found at Bovey. She says the utmost caution is needed in attempting to date one of the older Tertiary floras by its plant remains, because of the long range of most species shown by research on
Eocene and Oligocene plants. Her description is rather confusing and
FIG. 5.2. attempts to summarise this discussion. The Mastixia genus
Chandler considers to be worthy of special mention. It, or its close
allies, is among the most abundant Eocene plants ranging from the London
Clay to the Lower Headon (so far they have not been found in younger beds).
Chandler quotes Kirchheimer (1936), who worked on the German Brown Coal,
and concludes that Mastixia disappeared in Europe after the Oligocene.
Chandler therefore presumes that the sparse occurrence of Mastixia
boveyana, quite distinct from the older Eocene species, indicates a pre-
Miocene and post-Eocene age. From the foregoing discussions, Chandler
supposed the age to be Middle Oligocene. Except for Gardner (1879),
who did not even study the actual flora itself, all the Palaeobotanists
consider the age of the Bovey lignites to be Oligocene, although some
adjustment in the then Tertiary time scales is necessary in the case of
Pengelley and Heer.

Another point of interest from Chandler's work is the reference
to pollen. The Institute of Geological Sciences' recent borehole at
Petrockstowe has been subjected to pollen analysis by Turner, who has
shown that only the top 400 feet of the borehole is in fact Oligocene,
the remaining 1800 feet and the shelf area ball clays are in fact Eocene
in origin (Freshney - Personal Communication 1974). Samples of Bovey
boreholes have been supplied to the Institute of Geological Sciences
and the outcome of these investigations is awaited with interest.
Although it is likely that the age of the Bovey Coalpit Section of the
deposit is Oligocene, the Highest Sandy Member lies unconformably over
the lower members with marked angular disconformity on the western side
of the basin and may well be much younger - Miocene or even Pliocene in
age. Perhaps the comment made by earlier authors - that the Bovey Beds
fill a gap in the British Stratigraphic Column - may well be in part true.
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**FIG. 5.2** Summary of Chandler (1957) discussion on the age of the Bovey Flora

-90-
The large column of strata which exists below the known sequence, probably over 2000 feet in thickness, must consist of older Tertiary and possibly partly Cretaceous material so that the Bovey Basin may in fact have been filled over a considerable period of time, possibly representing a large part of the Tertiary Period.

5.11. After Scott (1929) the literature is sparse and almost wholly dealing with specialised topics which sometimes only include the Bovey Basin in passing, such as Blyth (1957). The remainder of the modern work tends to follow a similar trend. Dineley (1963) described "The Contortions in the Bovey Beds". Locally, the beds of clays and lignites are thrown into small sharp anticlynes, or domes. This fact was commented on by Pengelley (1862). Dineley, over the period 1951 to 1959, observed nine of these structures in detail as the pit faces were worked for clay and concludes that the contortions are periglacial disturbances of Pleistocene age. Plate 5.1. illustrates such a structure (which looks very similar to Dineley's drawings), showing the top beds of clay after removal of overburden for the working of Southacre Pit, circa 1953. Such contortions die out below 30 feet from the level of the 'heading'.

With such features in the shallow workings of the last century it is hardly surprising that Key (1861) and other authors describe very high dips, approaching vertical in many parts of the working sequence.

Bristow (1968), by means of a comparison of the X-Ray Diffraction traces from weathered Culm shales and North Devon ball clays, attempted to show the derivation of the latter from the former by a simple process of weathering. He concludes "There seems little doubt that the Tertiary sediments in the Petrockstow basin have originated in weathering mantle developed under humid sub-tropical or warm temperature conditions from Culm Measures shales and sandstones". The absence of granitic tourmaline sands from North Devon would tend to confirm Bristow's hypothesis but the same does not apply to the Bovey Basin, where the interbedded sands are of obvious granitic origin. Bristow's paper does however show that Maw's 1867 paper was not a complete 'red herring' and quite probably the surrounding country rock had some influence on the Bovey kaolinites, but certainly not to the degree envisaged by Bristow at Petrockstow.

The next paper dealt with "Some Geotechnical and Sedimentary Aspects of Ball Clays from Devon" and was by Best & Fookes (1970). Small-scale sedimentological structures were considered to show a fluvio-lacustrine environment and the difference in consistency between the stoneware and whiteware clays was considered to have arisen as a result of variations in the intensity of desiccation to which individual beds of ball clay were subjected shortly after deposition, when receding floodwaters allowed drying of the fresh sediment. Unfortunately, unlike Petrockstow, the present author has not seen desiccation cracks in the Bovey ball clays to support this hypothesis. Best & Fookes show the clays to be overconsolidated and conclude that this could only be due to:
(a) desiccation shortly after deposition

or (b) secondary consolidation on a geological time scale implying that depth of burial was once far greater and has since been removed by erosion.

There is no positive evidence for either mechanism. Bjerrum (1957) discusses the concept of delayed or secondary consolidation. Obviously, individual clay layers suffer settlement as the deposits gradually build up and they become loaded with the overlying sediments. Bjerrum considers that settlement would continue after the excess pore pressures set up during deposition had dissipated and the clay structure effectively supported the overburden pressure. He also considered that this settlement would continue for thousands of years. Might this concept explain the overconsolidation of the Bovey ball clays, which are at least 30 million years old?

Bristow and Hughes (1969 and 1971) describe thrust faulting on the southern margin of the Bovey Basin. The thrust was recognised in workings around Mainbow and Ringslade ball clay workings belonging to E.C.C. Ball Clays, the authors being members of E.C.C.'s Geological Department. Some limited evidence for the thrust can be detected in boreholes of the Devon & Courtenay Clay Company Limited (a constituent Company of the WBB Group) further to the south at the foot of Whitehill and Knowles Hill. The boreholes logged 'shales' overlying the clays but were sunk before the merger between the two Companies, and prior to the present author's engagement, and further investigation did not take place. It was not until Bristow and Hughes' description in 1969 that the significance of these earlier boreholes was recognised.

Prior to January 1974, the final paper published generally concerning the Bovey Basin was published in 1971. This paper was by Fasham and was based on a gravity survey of the Bovey Basin as a PhD topic. At the time of the readings being taken, Fasham had the
co-operation of the ball clay companies and much discussion took place. Fasham produced a model of the rock basin which showed:

1. a depth of some 4200 feet (1300 metres)
2. a large fault running parallel to the Sticklepath trend on the western margin
3. that the depth contour line showed general parallelism to the outcrops of the various strata.

Fasham and the present author had long discussions regarding the density of the Bovey Beds and the depth-density variation. For want of more definite evidence, the proven density data at Petrockstow was used, on the assumption that the lithologies were similar. In the construction of the model the constant term in the equation was taken as 2.0 to conform with the surface density of 2 g/cc observed by Best & Fookes (1969 - Preliminary Results of their 1970 Paper). Also, for depths greater than 2000 feet (610 metres) - the depth of the Petrockstow Basin - a constant density, equal to the value predicted by the regression equation at 2000 feet, was used. Unfortunately the lithologies of the two basins are dissimilar in one major respect - that is, in the occurrence of lignite. Lignite forms a very small part of the Petrockstow succession, yet forms a major element at Bovey. Of a recent borehole sunk at Bovey to over 1000 feet in depth, some 500 feet would have been classified as lignite. Such thicknesses of lower density material are bound to affect the gravity anomaly and reduce the constant term of 2.0 substantially, which would reduce the estimate of the overall depth of the basin. The present author considers the figure of 4200 feet to be too high and that the depth of the basin is nearer to 3500 feet. This is only likely to be proved by a deep borehole through the Tertiary strata into the rock basin. As such a borehole is unlikely to yield any information of commercial value, and would only be sunk at
considerable cost, it is difficult to visualise any activity of this nature by the clay companies.

Over the last few years, the University of Exeter, under contract to the Institute of Geological Sciences, has been engaged in remapping Sheet 339, which covers the Bovey Basin. The basin was covered by Edwards, who received borehole logs, plans and co-operation from the ball clay companies. After some discussion with Gouldstone and the present author, Edwards decided to call Scott's whiteware clays the 'Southacre' Member. One of W.B.B.'s largest opencast workings is named Southacre Pit, although the area of Southacre covers a wide area. The original Southacre pit and shaft described in STRAHAN (1920) and Scott (1929) were in fact some way to the north-east of the present working, and in a series of clays at the base of the main lignites. Fortunately these lower clays are within the Southacre Member. The siliceous clays (the 'stoneware' clays of Scott) presented Edwards with more difficult naming problem as the present main working area is referred to as "White Pit" - a descriptive rather than an area name. He decided to call these clays the 'Abbroom' Member, after an area further to the south where we agreed these clays had previously been worked. For the sake of clarity, these names have been adhered to by the present author.

The tracing of the Southacre Member is comparatively easy as far as Newbridge but it is obscure to the north of this location. Unfortunately both Edwards' (1970) interpretation of the Chudleigh Knighton clays and the present author's interpretation in a previous publication (Vincent, 1971) have been proved to be incorrect after further information became available. Edwards' continuation of the Southacre Member eventually to join into the Bovey "Coalpit" is also incorrect. Description of the stratigraphy, based on all the boring information available, including the most recent logs, is described in Chapter 6.
The last work available at the time of writing is contained in an unpublished PhD thesis by Saldivar-Sali (1973). He investigated small scale fissures in clay and devotes a section of one chapter (6.1.) to the Bovey ball clays (again with WBB's co-operation and some enjoyable discussions). Saldivar-Sali recognised fissures in the clays and describes the locations and directions of the fissures (although at times he appears to become a little confused with regard to which member he was in). He found some of the fissuring to be parallel to the Sticklepath direction (he attributes to Edwards, 1970 and Vincent, 1971, that the faults within the basins are normal faults, whilst in fact most of them are oblique slip) but does not consider that it is justifiable to analyse the fissure fabric wholly in terms of wrench-fault tectonics, and continues to show that the fissures could well be due to 'basining' (i.e. the downsinking of the strata during deposition). Saldivar-Sali discusses non-tectonic origins, such as deep burial with subsequent unloading and shrinkage, but favours the 'basining' hypothesis as the origin of these fissures.

5.12. This Chapter has reviewed what is known about the Bovey Basin. This can be summarised as follows:-

1. The Bovey Basin is in excess of 3500 feet deep.

2. It is tectonic in origin in association with the Sticklepath Fault System.

3. Provenance of the sands and the clays is agreed by most authors to be the Dartmoor granite.

4. The age of the "Coalpit" lignites is probably Middle Oligocene, but strata of younger and much older periods are probably contained within the Bovey Basin.
5. Although the sedimentology of the sands and the lignites is discussed to a limited extent, the fine particle size of the clays and their sedimentology are not discussed by any previous author.

It is with conclusions 3 and 5 that this thesis is mainly concerned.
6. THE STRATIGRAPHY AND STRUCTURE OF THE BOVEY BASIN.

6.1. The outcrop of the main ball clay-bearing beds has been well known since the Eighteenth Century. It stretches from Chudleigh Knighton around the eastern side of the basin to Newton Abbot and south to Decoy where the dip was recognised to be to the east rather than to the west. A two-fold division was noted comparatively early and was identified by Scott (1929) as being the 'whiteware beds' and the 'stoneware beds'. Edwards (1970) identified these groups as the Southacre and Abbrook Members respectively and, in addition, recognised the Blatchford Member in the southern part of the main basin. Vincent (1971) introduced further members and sub-members (or facies), such as the Heathfield Member, the Twinyeo Member, the Chudleigh Knighton Facies and the West Golds Facies (equivalent to Edwards's Blatchford Member). In the light of further boring evidence, considerable modifications are necessary to the fairly simple interpretations of the upper part of the Bovey Basin. The overall stratigraphy is illustrated in a series of sections comprising FIG. 6.1. and the outcrop patterns and geological setting are shown in FIG. 6.2. Both these figures are contained in a pocket at the back of the thesis.

Although the Bovey Basin probably includes the Aller Gravels and Greensand as well as a considerable thickness of unknown material which does not reach outcrop, the lowest member identified in FIG. 6.1. is the Lappathorn Member. As most commercial boreholes are stopped soon after hitting the upper part of this member, the complete section of this member is not known. Generally, it is a series of muddy silty sands and red mottled silty clays. The highly coloured clays at Ringslade were commented on by Best & Fookes (1970) who considered the mottling to be evidence for oxidising conditions within the sediments and desiccation soon after deposition. The Ringslade clays are most likely part of the
same member which is better developed on the eastern side of the basin, particularly in the Lappathorn Copse area after which the member is named.

6.2. Overlying the Lappathorn Member, probably with considerable unconformity (for which there is little evidence), is the Abbrook Member. This member is well known from Chudleigh Knighton in the North to Zitherixon and East Golds in the south and is one of the least variable of the members, although sand dominates the northern area more so than further south. This member consists of silty clays, clayey silts and muddy silty sands. Carbonaceous material is comparatively rare, except for a small band of lignitic clay in the middle of the sequence, and a group of brown clays with occasional thin lignite bands developed in the upper part of the member towards the south. The final phase of deposition is very silty clay, silts and silty sands which thin towards the south where the lignites of the overstepping Southacre Member are separated from the carbonaceous clays of the Abbrook Member by only some 4 feet of clayey silt.

The variations in the member are illustrated in FIG. 6.3, which is contained in a pocket at the back of the thesis.

The carbonaceous clays of this member show a trend which becomes dominant in the overlying Southacre Member. In the Chudleigh Knighton area, this section is represented by silty sand with some fawn siliceous clays. Towards the south the sand decreases and fawn-brown clay increases with the development of thin lignite bands. In the Southacre area the section is brown clays with subordinate lignites which further increase towards the south. At East Golds the section is lignite with brown carbonaceous clay seams.

The Abbrook Member varies from 39.5 metres (130 feet) to 52 metres (170 feet) in thickness. The type area however has not been
worked recently and very little information is available, the best-known sequence occurring at White Pit (to the east of Southacre).

The sequence in this area is as follows:

<table>
<thead>
<tr>
<th>Description</th>
<th>METRES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fawn-brown hawsy clay with increasing silt towards the base</td>
<td>2.14</td>
</tr>
<tr>
<td>Dense grey clayey silt with numerous quartz sand grains</td>
<td>1.52</td>
</tr>
<tr>
<td>Grey hawsy clay containing silt and sand particles</td>
<td>3.05</td>
</tr>
<tr>
<td>Grey dense clayey silt</td>
<td>0.53</td>
</tr>
<tr>
<td>Muddy silty sand</td>
<td>0.61</td>
</tr>
<tr>
<td>Grey hawsy slightly silty clay</td>
<td>1.44</td>
</tr>
<tr>
<td>Brown smooth hawsy clay with lighter and darker streaks, with numerous lignitised twigs, and occasional thin bands of lignite</td>
<td>3.50</td>
</tr>
<tr>
<td>Grey clayey silt</td>
<td>2.50</td>
</tr>
<tr>
<td>Grey slightly silty clay</td>
<td>1.22</td>
</tr>
<tr>
<td>Grey silt with some clay</td>
<td>0.36</td>
</tr>
<tr>
<td>Muddy silty sand</td>
<td>0.69</td>
</tr>
<tr>
<td>Dense grey clayey silt</td>
<td>0.82</td>
</tr>
<tr>
<td>Grey-fawn silty clay</td>
<td>1.46</td>
</tr>
<tr>
<td>Muddy silty sand</td>
<td>2.44</td>
</tr>
<tr>
<td>Grey hawsy slightly silty clay</td>
<td>4.51</td>
</tr>
<tr>
<td>Dense clayey silt</td>
<td>0.70</td>
</tr>
<tr>
<td>Grey-fawn hawsy smooth clay gradually becoming fawn towards the base</td>
<td>2.29</td>
</tr>
<tr>
<td>Lignitic clay to clayey lignite</td>
<td>0.15</td>
</tr>
<tr>
<td>Fawn clay full of lignitised plant remains</td>
<td>0.20</td>
</tr>
<tr>
<td>Grey dense very silty clay to clayey silt</td>
<td>3.05</td>
</tr>
<tr>
<td>Muddy silty sand</td>
<td>0.91</td>
</tr>
<tr>
<td>Grey silty clay, silt content increasing towards the base</td>
<td>2.13</td>
</tr>
<tr>
<td></td>
<td>METRES</td>
</tr>
<tr>
<td>------------------</td>
<td>--------</td>
</tr>
<tr>
<td>Grey clayey silt</td>
<td>0.61</td>
</tr>
<tr>
<td>Muddy silty sand</td>
<td>0.91</td>
</tr>
<tr>
<td>Grey clayey silt</td>
<td>2.44</td>
</tr>
<tr>
<td></td>
<td>40.19</td>
</tr>
<tr>
<td></td>
<td>(131'11&quot;)</td>
</tr>
</tbody>
</table>

Almost all the clays in this member exhibit mundic stain to a greater or lesser extent and occasionally siderite concretions or spherules are developed.

6.3. The other commercially important ball clay member is the Southacre Member. This member is dominated by a tripartite facies differentiation around the eastern outcrop with dominantly sands in the north from Little Bradley towards Chudleigh Knighton Heath, a clay facies stretching from Chudleigh Knighton Heath through the Clay Lane area towards Twinyeo, and a lignite facies from Twinyeo continuing south to East Golds, and probably also to the Decoy area to the south of Newton Abbot. The variations in this member are also illustrated in FIG. 6.3.

The initial sedimentary area stretched from Little Bradley to south of Southacre and commenced with a lignite band over the whole area, followed by carbonaceous clays which run to lignites in the south. The next phase runs from sand in the north, through grey clays to carbonaceous clays and lignites in the south. The Middle Southacre lignites overstep to the south to rest directly on the carbonaceous clays of the Abbrook Member. The upper part of the member shows some variations in the broad overall pattern with carbonaceous clays and non-carbonaceous clays; with occasional silty sands, associated with numerous seams of lignite developing in the southern part of the area. This clay/lignite facies is overstepped to the south by the Blatchford and Stover Members and, to
the north, the Twinyeo Member lenses in between the Stover and Southacre Members. The best development of the upper part of the member occurs in the Southacre area which, contrary to the general pattern, becomes much more lignitic in the north towards Twinyeo although, beyond this area, clay and eventually sand are found on this horizon. One of the final Southacre seams, known as 'Parks', is characterised by well-ordered kaolinite, low alkalis and abundant siderite, and forms one of the major marker bands of the Bovey Basin. The recognition of a member which can be almost completely clay, lignite or sand would be impossible in boreholes remote from the eastern outcrop without the Parks Seam.

The boring in the Ventiford and Stover Park areas indicates that the Upper Southacre clays become much more silty with the intermittent sand beds becoming more dominant, indicating that sediment was being derived not only from the north but also from the west or north-west.

The Southacre Member is approximately 60 metres (200 feet) thick in the type area but reaches 73 metres (240 feet) in Borehole 660 where it is almost exclusively lignite. On Chudleigh Knighton Heath, and presumably to the north-west, the Southacre Member is covered by 40 metres (130 feet) of sand which may be an entirely separate member or a continuation of the Southacre Member over a shrinking sedimentary area. As these sands are apparently overstepped by the Twinyeo Member, the latter premise is considered to be the most likely.

The sequence in the type area is as follows:

<table>
<thead>
<tr>
<th>METRES</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fawn to brown slightly silty clays with some lignitised twigs and plant remains</td>
<td>1.52 (5' 0&quot;)</td>
</tr>
<tr>
<td>Brown disturbed clays with thin lignite bands and lignitised plant remains</td>
<td>3.35 (11' 0&quot;)</td>
</tr>
<tr>
<td>Grey-fawn slightly silty clay with some mordic stain</td>
<td>0.91 (3' 0&quot;)</td>
</tr>
<tr>
<td>Description</td>
<td>METRES</td>
</tr>
<tr>
<td>----------------------------------------------------------------------------</td>
<td>--------</td>
</tr>
<tr>
<td>Fine clayey silty sand</td>
<td>0.30   (1' 0&quot;)</td>
</tr>
<tr>
<td>Dense grey-fawn clay with yellow fine laminations of powdery siderite and lignitised plant remains, mainly leaves and ferns (Parks Seam).</td>
<td>4.27   (14' 0&quot;)</td>
</tr>
<tr>
<td>Clayey lignite</td>
<td>0.46   (1' 6&quot;)</td>
</tr>
<tr>
<td>Grey-fawn smooth clay (Parks Seam)</td>
<td>0.30   (3' 0&quot;)</td>
</tr>
<tr>
<td>Clayey lignite</td>
<td>1.07   (3' 6&quot;)</td>
</tr>
<tr>
<td>Dark brown streaky clay full of lignitised plant remains</td>
<td>3.05   (10' 0&quot;)</td>
</tr>
<tr>
<td>Lignite</td>
<td>0.23   (0' 9&quot;)</td>
</tr>
<tr>
<td>Brown smooth clay with some lignitised plant remains</td>
<td>1.49   (4' 9&quot;)</td>
</tr>
<tr>
<td>Lignite with clay bands</td>
<td>0.76   (2' 6&quot;)</td>
</tr>
<tr>
<td>Brown disturbed clay</td>
<td>1.37   (4' 6&quot;)</td>
</tr>
<tr>
<td>Clayey lignite</td>
<td>0.31   (1' 0&quot;)</td>
</tr>
<tr>
<td>Dense brown lignitic clay</td>
<td>0.76   (2' 6&quot;)</td>
</tr>
<tr>
<td>Lignite</td>
<td>1.07   (3' 6&quot;)</td>
</tr>
<tr>
<td>Brown silty clay with some lignitised plant remains and thin lashes of silty sand</td>
<td>5.03   (16' 6&quot;)</td>
</tr>
<tr>
<td>Clayey lignite</td>
<td>0.61   (2' 0&quot;)</td>
</tr>
<tr>
<td>Very lignitic clay</td>
<td>0.91   (3' 0&quot;)</td>
</tr>
<tr>
<td>Clayey lignite</td>
<td>0.61   (2' 0&quot;)</td>
</tr>
<tr>
<td>Very lignitic clay</td>
<td>0.31   (1' 0&quot;)</td>
</tr>
<tr>
<td>Lignite with occasional seams of lignitic clay crammed with plant remains</td>
<td>4.57   (15' 0&quot;)</td>
</tr>
<tr>
<td>Dense grey-fawn silty clay</td>
<td>1.52   (5' 0&quot;)</td>
</tr>
<tr>
<td>Brown to fawn smooth clay with some lignitised plant remains</td>
<td>0.61   (2' 0&quot;)</td>
</tr>
<tr>
<td>Dense fawn slightly silty clay with strands of lignite and lignitised plant remains</td>
<td>0.69   (2' 3&quot;)</td>
</tr>
<tr>
<td>Clayey lignite</td>
<td>0.54   (1' 9&quot;)</td>
</tr>
<tr>
<td>Lignitic clay crammed with plant remains</td>
<td>0.82   (2' 8&quot;)</td>
</tr>
<tr>
<td>Clayey lignite</td>
<td>0.41   (1' 4&quot;)</td>
</tr>
<tr>
<td>Description</td>
<td>Metres</td>
</tr>
<tr>
<td>---------------------------------------------------------------------------</td>
<td>--------</td>
</tr>
<tr>
<td>Dark brown lignitic clay crammed with lignitised plant remains and fine lignite bands</td>
<td>1.83 (6' 0&quot;)</td>
</tr>
<tr>
<td>Lignite</td>
<td>0.31 (1' 0&quot;)</td>
</tr>
<tr>
<td>Very lignitic clay</td>
<td>0.20 (0' 8&quot;)</td>
</tr>
<tr>
<td>Lignite</td>
<td>0.71 (2' 4&quot;)</td>
</tr>
<tr>
<td>Dense very lignitic clay with fine lignite bands</td>
<td>0.91 (3' 0&quot;)</td>
</tr>
<tr>
<td>Lignite</td>
<td>0.76 (2' 6&quot;)</td>
</tr>
<tr>
<td>Brown carbonaceous clay full of plant remains</td>
<td>0.31 (1' 0&quot;)</td>
</tr>
<tr>
<td>Lignite</td>
<td>1.37 (4' 6&quot;)</td>
</tr>
<tr>
<td>Lignitic clay and lignite</td>
<td>0.46 (1' 6&quot;)</td>
</tr>
<tr>
<td>Lignite with occasional clayey bands</td>
<td>6.55 (21' 6&quot;)</td>
</tr>
<tr>
<td>Dense lignitic clay</td>
<td>0.82 (2' 8&quot;)</td>
</tr>
<tr>
<td>Clay and lignite</td>
<td>0.15 (0' 6&quot;)</td>
</tr>
<tr>
<td>Lignite with occasional lignitic clay bands which, further to the north, reach substantial thickness</td>
<td>7.93 (26' 0&quot;)</td>
</tr>
<tr>
<td></td>
<td><strong>59.85 (199' 2&quot;)</strong></td>
</tr>
</tbody>
</table>

6.4. Overlying the Southacre Member with only a slight angular unconformity is another very lignitic member which is overstepped with considerable discordance by the Stover Member. Consequently the area of outcrop of this comparatively thick member is surprisingly limited. The only positively proved area of even limited outcrop so far found is in the Twinyeo area, after which the member is named. The thickest sequence (nearly 90 metres - 300 feet) so far penetrated of this member is in Boreholes 643 and 660 (Section 5, FIG. 6.1.) where the sequence is mainly lignites. Large thicknesses of lignite are also found under Bovey Heath in Borehole 650 (Section 4), Boreholes 647, 648 and 649 (Section 3) and Borehole 651 (Section 2). On Section 2, the Twinyeo Member runs to sand, both to the north-east and to the west.
The sequence in Borehole 660 is as follows:

<table>
<thead>
<tr>
<th>Description</th>
<th>Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grey to brown silty slightly sandy clay with lignitised plant remains</td>
<td>1.83</td>
</tr>
<tr>
<td>Muddy silty sand</td>
<td>0.91</td>
</tr>
<tr>
<td>Clayey lignite</td>
<td>0.91</td>
</tr>
<tr>
<td>Light brown silty sandy clay with traces of plant remains</td>
<td>2.44</td>
</tr>
<tr>
<td>Clayey lignite</td>
<td>0.91</td>
</tr>
<tr>
<td>Light brown sandy clay with fine lignite strands and laminations becoming</td>
<td>3.05</td>
</tr>
<tr>
<td>very sandy</td>
<td></td>
</tr>
<tr>
<td>Lignite with one thin clayey band</td>
<td>4.88</td>
</tr>
<tr>
<td>Light brown sideritic, silty and sandy clay with some plant remains and</td>
<td>11.28</td>
</tr>
<tr>
<td>occasional sand bands. This clay resembles Parks which occurs under-</td>
<td></td>
</tr>
<tr>
<td>lying the Twinyeo Member in this borehole</td>
<td></td>
</tr>
<tr>
<td>Lignite with some clayey bands</td>
<td>3.05</td>
</tr>
<tr>
<td>Brown clay with varying lignite and silt content</td>
<td>1.53</td>
</tr>
<tr>
<td>Lignite with occasional clay bands</td>
<td>2.44</td>
</tr>
<tr>
<td>Brown lignitic clay</td>
<td>0.61</td>
</tr>
<tr>
<td>Lignite</td>
<td>2.74</td>
</tr>
<tr>
<td>Grey-brown very sandy and silty clays with some mundic stain and</td>
<td>4.72</td>
</tr>
<tr>
<td>occasional thin lignite bands</td>
<td></td>
</tr>
<tr>
<td>Lignite and occasional thin clayey bands</td>
<td>1.37</td>
</tr>
<tr>
<td>Grey smooth clay with a trace of mundic stain</td>
<td>0.61</td>
</tr>
<tr>
<td>Lignite and some thin clayey bands</td>
<td>5.11</td>
</tr>
<tr>
<td>Muddy silty sand</td>
<td>0.99</td>
</tr>
<tr>
<td>Grey-fawn sandy clay with some mundic stain</td>
<td>1.83</td>
</tr>
<tr>
<td>Muddy silty sand</td>
<td>1.53</td>
</tr>
<tr>
<td>Lignite with occasional lignitic clay bands</td>
<td>19.20</td>
</tr>
<tr>
<td>Brown lignitic clay</td>
<td>2.44</td>
</tr>
</tbody>
</table>
### Metres

<table>
<thead>
<tr>
<th>Description</th>
<th>Metres</th>
<th>(Feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lignite</td>
<td>0.30</td>
<td>1' 0&quot;</td>
</tr>
<tr>
<td>Brown lignitic clay</td>
<td>0.46</td>
<td>1' 6&quot;</td>
</tr>
<tr>
<td>Lignite with occasional clay bands</td>
<td>5.33</td>
<td>17' 6&quot;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>80.47</td>
<td>264' 0&quot;</td>
</tr>
</tbody>
</table>

6.5. The focus of sedimentation moved further south after Twinnyeo times and the next member, as far as is known, does not appear to have been laid down very far to the north of the A38 trunk road which runs through the centre of the Bovey Basin from north-east to south-west.

This member is dominantly a sand member with subordinate clayey silts and silty, sandy clays, with only rare lignite bands. Further to the south, on the evidence of the Teigngrace borehole, the member assumes a 'clay' facies. Except for some limited evidence in the Denistone area, there is no confirmatory evidence as yet for the Stover Member clay facies. Further to the south again, the Stover Member is rapidly overstepped by the Blatchford Member and only the lowest part of the Stover Member is found as far south as East Golds.

In Borehole 223, the Stover Member is some 183 metres (600 feet) thick and may well in fact include part of one of the later members. Both this problem and the clay facies will be evaluated by future boring.

The sequence of the Stover Member in Borehole 223 is as follows:

### Metres

<table>
<thead>
<tr>
<th>Description</th>
<th>Metres</th>
<th>(Feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silty sand</td>
<td>11.27</td>
<td>37' 0&quot;</td>
</tr>
<tr>
<td>Grey sandy clay with some yellow stain</td>
<td>0.30</td>
<td>1' 0&quot;</td>
</tr>
<tr>
<td>Silty sand</td>
<td>5.48</td>
<td>18' 0&quot;</td>
</tr>
<tr>
<td>Grey-fawn silty sandy clay with some lignitised plant remains and occasional sand lashes</td>
<td>2.43</td>
<td>8' 0&quot;</td>
</tr>
<tr>
<td>Silty sand</td>
<td>6.09</td>
<td>20' 0&quot;</td>
</tr>
<tr>
<td>Description</td>
<td>Metres</td>
<td></td>
</tr>
<tr>
<td>----------------------------------------------------------------------------</td>
<td>---------</td>
<td></td>
</tr>
<tr>
<td>Grey-brown silty clay</td>
<td>1.52</td>
<td></td>
</tr>
<tr>
<td>Silty sand</td>
<td>2.13</td>
<td></td>
</tr>
<tr>
<td>Light grey silty sandy clay</td>
<td>0.91</td>
<td></td>
</tr>
<tr>
<td>Lignite</td>
<td>0.30</td>
<td></td>
</tr>
<tr>
<td>Muddy silty sand with lignitised twigs and branches</td>
<td>7.62</td>
<td></td>
</tr>
<tr>
<td>Lignitic clay</td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td>Brown slightly silty clay</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>Black lignitic clay</td>
<td>0.64</td>
<td></td>
</tr>
<tr>
<td>Muddy silty gravelly sand with fragments of felspar and abundant tourmaline</td>
<td>3.05</td>
<td></td>
</tr>
<tr>
<td>Brown slightly silty clay</td>
<td>0.54</td>
<td></td>
</tr>
<tr>
<td>Muddy silty gravelly sand</td>
<td>12.83</td>
<td></td>
</tr>
<tr>
<td>Grey clayey silt</td>
<td>0.91</td>
<td></td>
</tr>
<tr>
<td>Muddy silty gravelly sand</td>
<td>0.91</td>
<td></td>
</tr>
<tr>
<td>Grey extremely silty clay</td>
<td>1.37</td>
<td></td>
</tr>
<tr>
<td>Muddy silty gravelly sand</td>
<td>1.76</td>
<td></td>
</tr>
<tr>
<td>Grey to brown clayey silt with numerous sub-hedral quartz corns</td>
<td>0.61</td>
<td></td>
</tr>
<tr>
<td>Silty sand</td>
<td>2.43</td>
<td></td>
</tr>
<tr>
<td>Brown sandy clay</td>
<td>2.74</td>
<td></td>
</tr>
<tr>
<td>Silty sand</td>
<td>6.09</td>
<td></td>
</tr>
<tr>
<td>Grey silty sandy clay with some mundic stain and numerous sub-hedral quartz corns</td>
<td>6.09</td>
<td></td>
</tr>
<tr>
<td>Silty sand with a band of lignitic clay and lignitised plant remains</td>
<td>11.88</td>
<td></td>
</tr>
<tr>
<td>Grey-fawn silty clay becoming slightly silty with somemundic stain and siderite</td>
<td>5.48</td>
<td></td>
</tr>
<tr>
<td>Brown slightly silty clay with traces of lignitised wood and siderite</td>
<td>0.46</td>
<td></td>
</tr>
<tr>
<td>Lignite with some lignitic clay</td>
<td>2.43</td>
<td></td>
</tr>
<tr>
<td>Grey-fawn clay full of siderite sand</td>
<td>1.98</td>
<td></td>
</tr>
<tr>
<td>Silty sand</td>
<td>6.09</td>
<td></td>
</tr>
<tr>
<td>Brown smooth clay with some lignitised plant remains and siderite</td>
<td>0.46</td>
<td></td>
</tr>
<tr>
<td>Description</td>
<td>Metres</td>
<td>(Feet)</td>
</tr>
<tr>
<td>-----------------------------------------------------------------------------</td>
<td>---------</td>
<td>---------</td>
</tr>
<tr>
<td>Grey sandy clay</td>
<td>4.11</td>
<td>13' 6&quot;</td>
</tr>
<tr>
<td>Silty sand</td>
<td>2.59</td>
<td>8' 6&quot;</td>
</tr>
<tr>
<td>Grey to brown sandy clay with occasional lignitic bands</td>
<td>1.52</td>
<td>5' 0&quot;</td>
</tr>
<tr>
<td>Silty sand</td>
<td>10.36</td>
<td>34' 0&quot;</td>
</tr>
<tr>
<td>Grey sandy clay to very sand clay with occasional lignitised plant remains</td>
<td>7.62</td>
<td>25' 0&quot;</td>
</tr>
<tr>
<td>Silty sand</td>
<td>5.18</td>
<td>17' 0&quot;</td>
</tr>
<tr>
<td>Lignitic clay</td>
<td>0.40</td>
<td>1' 6&quot;</td>
</tr>
<tr>
<td>Lignite and lignitic clay</td>
<td>0.30</td>
<td>1' 0&quot;</td>
</tr>
<tr>
<td>Grey sandy clay</td>
<td>2.59</td>
<td>8' 6&quot;</td>
</tr>
<tr>
<td>Brown slightly silty clay with considerable lignitised plant remains</td>
<td>1.52</td>
<td>5' 0&quot;</td>
</tr>
<tr>
<td>Lignite</td>
<td>1.22</td>
<td>4' 0&quot;</td>
</tr>
<tr>
<td>Silty sand</td>
<td>6.10</td>
<td>20' 0&quot;</td>
</tr>
<tr>
<td>Grey (red and yellow mottled at the base) sandy clay</td>
<td>2.13</td>
<td>7' 0&quot;</td>
</tr>
<tr>
<td>Silty sand</td>
<td>1.22</td>
<td>4' 0&quot;</td>
</tr>
<tr>
<td>Clayey silty sand</td>
<td>0.61</td>
<td>2' 0&quot;</td>
</tr>
<tr>
<td>Grey-fawn slightly sandy clay</td>
<td>0.76</td>
<td>2' 6&quot;</td>
</tr>
<tr>
<td>Lignite</td>
<td>0.61</td>
<td>2' 0&quot;</td>
</tr>
<tr>
<td>Brown smooth clay with much lignitised plant remains</td>
<td>0.76</td>
<td>2' 6&quot;</td>
</tr>
<tr>
<td>Silty sand</td>
<td>3.35</td>
<td>11' 0&quot;</td>
</tr>
<tr>
<td>Grey slightly silty sand with occasional sandy lassles</td>
<td>2.13</td>
<td>7' 0&quot;</td>
</tr>
<tr>
<td>Brown disturbed clay</td>
<td>2.05</td>
<td>10' 0&quot;</td>
</tr>
<tr>
<td>Silty sand</td>
<td>0.91</td>
<td>3' 0&quot;</td>
</tr>
<tr>
<td>Sandy clayey silt</td>
<td>0.46</td>
<td>1' 6&quot;</td>
</tr>
<tr>
<td>Grey and grey-brown silty and sandy clay</td>
<td>3.81</td>
<td>12' 6&quot;</td>
</tr>
<tr>
<td>Silty sand</td>
<td>3.96</td>
<td>13' 0&quot;</td>
</tr>
<tr>
<td>Grey-fawn sandy clay</td>
<td>0.91</td>
<td>3' 0&quot;</td>
</tr>
<tr>
<td>Silty sand</td>
<td>4.88</td>
<td>16' 0&quot;</td>
</tr>
<tr>
<td>Grey silty clay</td>
<td>0.91</td>
<td>3' 0&quot;</td>
</tr>
</tbody>
</table>
6.6. The southern part of the main basin has a synclinal structure with a steeply inclined western limb. The upper part of this syncline is filled with silty gravelly sands, of obvious granite origin, which reach over 91 metres (300 feet) in the Blatchford and West Golds area, the member being named after the former area by Edwards (1970).

In the extreme south of the area, the Blatchford Member rests directly on the Southacre Member but, further north, some of the Lower Stover Member is found. The overstep of the Blatchford Member onto the Stover Member is abrupt and is based on the evidence of the Teigngrace Borehole which is mainly silty and sandy clays in the upper part and only penetrates sand in the lowest part of the Stover Member. However Borehole 623, some 427 metres (1400 feet) to the east of the Teigngrace Borehole, penetrates 67 metres (220 feet) of Blatchford sands. Without the evidence of the Teigngrace Borehole, the Blatchford sands would probably be correlated with the Upper Stover Member. However, as such evidence cannot be ignored, the correct relationships of the Blatchford Member to the Stover Member and other later members are obscure and correlation is awaited from further boring.

Exposures of the member are rare although a limited exposure can be seen on the back edge of Newton Abbot Clays Pit at East Golds. The material is usually washed out during the boring operation (this member presents problems which have largely been overcome by wireline techniques - Vincent, 1971) but, where sufficient clay occurs to 'bind'
the sand together, cores of the looser sands are sometimes retained above the 'clayey' lash. The drilling fluid also returns cuttings to the top of the borehole and usually results in a large pile of sand beside the machine. From the evidence available, the Blatchford Member is gravelly, silty, often muddy sand with occasional clayey areas. The sands are sub-hedral quartz, showing little evidence of transport, usually with tourmaline included in the individual quartz grains and as an accessory. It is almost impossible to differentiate between a sample of washed sand from the Company's china clay workings and a washed sand from the Blatchford Member. All the sands so far seen in the other members, including residues in the clays, are similar in character and are considered to be of granitic origin.

6.7. The focus of sedimentation so far has been towards the eastern side of the basin with the sedimentation area covering most of the eastern Bovey Basin during much of the Abbrook and Southacre times. The sedimentary area shrank towards the end of Southacre times and moved to the north throughout Twinyeo times, only to move south during Stover times and finally to the extreme south of the basin during Blatchford times. At the end of this period of time, and after the lapse of an unknown period, sedimentation recommenced but to the north and west of the previous area, so that a considerable unconformity exists between the Brimley Member and the underlying members (see FIGS. 6.1. and 6.2.).

The Brimley Member is a lignitic member initially but is dominantly sand in its upper part. This member includes Pengelley's Coal Pit Section which is to the south-west of Bovey Tracey. The area is generally known today as the Brimley area although Higher and Lower Brimley and Brimley are further to the west (see FIG. 6.2.). The member has, for want of a better name, been called the Brimley Member as this is the only proven area of outcrop.
The Brimley Member has only been proved as far south as
Section 5 (see FIGS. 6.1. and 6.2.) where this diminishing sequence
rests on the northward feathering Stover Member. Further to the
north, the Brimley Member rests directly on thick Twinyeo lignites
which feather to the west and run to sand towards the north. On
the evidence of the German boreholes (described in Strahan, 1920, and
Scott, 1929) and Borehole 651, a considerable fault affects this member
between German Boreholes 3 and 4 (see Section 2, FIG. 6.1.). This
fault apparently has a throw of approximately 122 metres (400 feet) and
apparently affects all members, including the youngest member, indicating
that movement was entirely post-depositional. The direction of the
fault is not clear but the insertion of a fault between Boreholes 640
and 641 on Section 4 (FIG. 6.1.) eases the correlation difficulties in
the lower part of Borehole 641. This borehole did not penetrate further
due to drilling difficulties which are often experienced in faulted sandy
sequences. Similar problems were also experienced in Borehole 659 at
the extreme western end of Section 5. These three points lie on a
straight line (see FIG. 6.2.) with a north-west to south-east trend
which, possibly coincidentally, is parallel to the Sticklepath Fault
trend. Consequently, the line of this large fault has been drawn on
FIG. 6.2. as being parallel to the Sticklepath trend. It is interesting
to note that a continuation and projection of this line cuts the boundary
of the Bovey Basin near Staplehill, where a substantial fault is already
known to exist, albeit apparently with a different trend.

A noticeable trend on Section 4 (FIG. 6.1.) is that the Brimley
Member lignitic facies becomes more sandy and clayey towards the west and
lignite seams diminish considerably. Pengelley's Coal Pit Section does
not represent the thickest lignite development of the Brimley Member
which occurs further to the east, although the outcrop is largely hidden
by the overstepping of the final member. The member is best known along
Section 4 where the tripartite sand-clay-lignite facies development can be recognised as occurring from west to east. The initial sand facies is considered to have occurred further to the west (outside the present boundaries of the Bovey Basin) and subsequently removed after uplift along the large western boundary fault. Possibly the sand facies of the Brimley Member and the overlying members have contributed material to the youngest member.

Along Section 4 the thickness of the Brimley Member varies from 73 metres (240 feet) to 104 metres (340 feet). Although the sequence on Borehole 642 is not the thickest, it is typical of the Brimley Member. That sequence is as follows:

<table>
<thead>
<tr>
<th>METRES</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.61</td>
<td>Brown clay with lignitised plant remains</td>
</tr>
<tr>
<td>0.51</td>
<td>Lignite and lignitic clay</td>
</tr>
<tr>
<td>1.32</td>
<td>Grey-blue sandy clay with heavy munding stain</td>
</tr>
<tr>
<td>0.76</td>
<td>Silty sand</td>
</tr>
<tr>
<td>2.29</td>
<td>Dense grey sandy sideritic clay with brownish bands and lignite strands</td>
</tr>
<tr>
<td>1.21</td>
<td>Silty sand</td>
</tr>
<tr>
<td>2.06</td>
<td>Purple-grey to purple-brown silty sandy clay with occasional lilac streaks</td>
</tr>
<tr>
<td>0.38</td>
<td>Fawn-brown clay becoming lignitic</td>
</tr>
<tr>
<td>0.30</td>
<td>Lignite</td>
</tr>
<tr>
<td>0.91</td>
<td>Brown silty lignitic clay with numerous thin lignitic strands</td>
</tr>
<tr>
<td>0.30</td>
<td>Grey slightly silty clay</td>
</tr>
<tr>
<td>1.40</td>
<td>Brown lignitic clay with numerous lignite strands</td>
</tr>
<tr>
<td>0.43</td>
<td>Lignite</td>
</tr>
<tr>
<td>2.36</td>
<td>Light brown smooth clay becoming darker in colour and sandy</td>
</tr>
<tr>
<td>0.08</td>
<td>Lignite</td>
</tr>
<tr>
<td>Description</td>
<td>METRES</td>
</tr>
<tr>
<td>-----------------------------------------------------------------------------</td>
<td>----------</td>
</tr>
<tr>
<td>Lost core - sand or lignite ?</td>
<td>1.83 (6' 0&quot;)</td>
</tr>
<tr>
<td>Grey-brown silty clay with some purple stain and bands of sand</td>
<td>3.86 (12' 8&quot;)</td>
</tr>
<tr>
<td>Lignite</td>
<td>0.71 (2' 4&quot;)</td>
</tr>
<tr>
<td>Brown lignitic clays with bands of solid lignite and clayey lignite</td>
<td>2.74 (9' 0&quot;)</td>
</tr>
<tr>
<td>Lignite</td>
<td>0.76 (2' 6&quot;)</td>
</tr>
<tr>
<td>Brown smooth clay full of lignitised plant remains and with occasional clayey lignite bands</td>
<td>1.67 (5' 6&quot;)</td>
</tr>
<tr>
<td>Brown lignitic clay with variable silt content, full of lignite bands and strands</td>
<td>1.98 (6' 6&quot;)</td>
</tr>
<tr>
<td>Lignite with brown smooth clay bands</td>
<td>3.66 (12' 0&quot;)</td>
</tr>
<tr>
<td>Brown lignitic clay with lignite strands</td>
<td>2.29 (7' 6&quot;)</td>
</tr>
<tr>
<td>Lignite with occasional clayey lignite bands</td>
<td>3.05 (10' 0&quot;)</td>
</tr>
<tr>
<td>Brown clay crammed with lignitised plant remains and with numerous clayey lignite bands</td>
<td>2.44 (8' 0&quot;)</td>
</tr>
<tr>
<td>Lignite</td>
<td>0.69 (2' 3&quot;)</td>
</tr>
<tr>
<td>Brown sandy clay</td>
<td>0.23 (0' 9&quot;)</td>
</tr>
<tr>
<td>Brown muddy silty sand full of lignitised plant remains</td>
<td>0.20 (0' 8&quot;)</td>
</tr>
<tr>
<td>Brown silty clay</td>
<td>0.41 (1' 4&quot;)</td>
</tr>
<tr>
<td>Brown lignitic clay with numerous lignite bands and sand lashes</td>
<td>3.05 (10' 0&quot;)</td>
</tr>
<tr>
<td>Brown lignitic clay with lignite bands</td>
<td>1.83 (6' 0&quot;)</td>
</tr>
<tr>
<td>Clayey lignite</td>
<td>1.22 (4' 0&quot;)</td>
</tr>
<tr>
<td>Lignitic clay with lignite bands</td>
<td>1.07 (3' 6&quot;)</td>
</tr>
<tr>
<td>Clayey lignite</td>
<td>1.22 (4' 0&quot;)</td>
</tr>
<tr>
<td>Dark brown clay crammed with plant remains</td>
<td>1.22 (4' 0&quot;)</td>
</tr>
<tr>
<td>Clayey lignite</td>
<td>0.30 (1' 0&quot;)</td>
</tr>
<tr>
<td>Brown lignitic clay</td>
<td>0.61 (2' 0&quot;)</td>
</tr>
<tr>
<td>Lignite, clayey lignite and lignitic clay</td>
<td>2.44 (8' 0&quot;)</td>
</tr>
<tr>
<td>Brown clay with lignitic areas with considerable lignitised plant remains</td>
<td>3.05 (10' 0&quot;)</td>
</tr>
<tr>
<td>Description</td>
<td>METRES</td>
</tr>
<tr>
<td>-----------------------------------------------------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>Lignite and clayey lignite</td>
<td>3.66</td>
</tr>
<tr>
<td>Brown clay with lignitised plant remains</td>
<td>1.40</td>
</tr>
<tr>
<td>Lignite</td>
<td>0.43</td>
</tr>
<tr>
<td>Lignitic clay with lignite bands</td>
<td>1.30</td>
</tr>
<tr>
<td>Brown smooth clay with plant remains</td>
<td>0.76</td>
</tr>
<tr>
<td>Lignitic clay and clayey lignite</td>
<td>0.99</td>
</tr>
<tr>
<td>Lignite with occasional clayey bands</td>
<td>4.88</td>
</tr>
<tr>
<td>Lignitic clay with lignite strands</td>
<td>0.91</td>
</tr>
<tr>
<td>Lignite</td>
<td>0.91</td>
</tr>
<tr>
<td>Lignitic clay</td>
<td>0.61</td>
</tr>
<tr>
<td>Lignite with occasional clayey areas</td>
<td>7.16</td>
</tr>
<tr>
<td>Dense brown slightly silty clay</td>
<td>0.30</td>
</tr>
<tr>
<td>Lignite</td>
<td>0.46</td>
</tr>
<tr>
<td>Brown lignitic clay with lignite and clayey lignite bands</td>
<td>3.50</td>
</tr>
<tr>
<td>Lignite with occasional clayey areas</td>
<td>1.37</td>
</tr>
<tr>
<td></td>
<td>86.09</td>
</tr>
</tbody>
</table>

6.8. Overlying the Brimley Member with little apparent unconformity is the Heathfield Member which has the smallest depositional area of any of the members. It is generally overlapped completely to the west and only outcrops in a narrow band at Heathfield, on the northern side of the A38 trunk road, and at Higher Brocks Plantation on the south side. This member is one of the few instances of the younger members being worked for clay, the working being carried out by Candy & Company Limited in the Heathfield Pit. This pit has now been abandoned for a number of years. The Heathfield borehole, described by Jukes-Brown (1909), Ussher (1913), Strahan (1920) and Scott (1929), was bored from the bottom of this pit. The more recent boring shows the upper part of this limited member to be mainly brown clays with occasional lignites, becoming more
sandy in the lower part. The member is approximately 40 metres (130 feet) in thickness and Borehole 643 (Section 5, FIG. 6.1.) shows a typical sequence.

<table>
<thead>
<tr>
<th>Description</th>
<th>Metres</th>
<th>(Feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chocolate brown silty clay</td>
<td>0.91</td>
<td>(3' 0&quot;)</td>
</tr>
<tr>
<td>Grey-fawn becoming silty and sandy clay</td>
<td>0.76</td>
<td>(2' 6&quot;)</td>
</tr>
<tr>
<td>Chocolate brown smooth lignitic clay with strands of lignite</td>
<td>1.52</td>
<td>(5' 0&quot;)</td>
</tr>
<tr>
<td>Grey-blue silty sandy clay full of mundic stain</td>
<td>1.52</td>
<td>(5' 0&quot;)</td>
</tr>
<tr>
<td>Grey clayey sandy silt</td>
<td>1.07</td>
<td>(3' 6&quot;)</td>
</tr>
<tr>
<td>Brown slightly sandy clay with some mundic stain</td>
<td>0.69</td>
<td>(2' 3&quot;)</td>
</tr>
<tr>
<td>Grey-blue clay blotched with mundic stain</td>
<td>1.30</td>
<td>(4' 3&quot;)</td>
</tr>
<tr>
<td>Light grey sandy clay with occasional lignite strands</td>
<td>0.46</td>
<td>(1' 6&quot;)</td>
</tr>
<tr>
<td>Light brown smooth clay</td>
<td>0.46</td>
<td>(1' 6&quot;)</td>
</tr>
<tr>
<td>Lignitic clay and lignite</td>
<td>0.38</td>
<td>(1' 3&quot;)</td>
</tr>
<tr>
<td>Brown smooth to slightly silty clay with considerable lignitised plant remains and bands of lignitic clay and clayey lignite</td>
<td>7.85</td>
<td>(25' 9&quot;)</td>
</tr>
<tr>
<td>Clayey lignite</td>
<td>1.52</td>
<td>(5' 0&quot;)</td>
</tr>
<tr>
<td>Dark chocolate brown clay crammed with plant remains</td>
<td>1.52</td>
<td>(5' 0&quot;)</td>
</tr>
<tr>
<td>Silty sand and lignitic material</td>
<td>3.96</td>
<td>(13' 0&quot;)</td>
</tr>
<tr>
<td>Light fawn silty and sandy clay</td>
<td>0.91</td>
<td>(3' 0&quot;)</td>
</tr>
<tr>
<td>Lignitic clay with strands of lignite</td>
<td>0.81</td>
<td>(2' 8&quot;)</td>
</tr>
<tr>
<td>Light brown to fawn silty clay containing lignitised plant remains</td>
<td>1.32</td>
<td>(4' 4&quot;)</td>
</tr>
<tr>
<td>Blue-grey extremely silty clay to clayey silt</td>
<td>0.91</td>
<td>(3' 0&quot;)</td>
</tr>
<tr>
<td>Grey-fawn silty clay with some mundic stain and lignitised twigs</td>
<td>2.74</td>
<td>(9' 0&quot;)</td>
</tr>
<tr>
<td>Brown silty clay full of plant remains becoming lignitic</td>
<td>2.13</td>
<td>(7' 0&quot;)</td>
</tr>
</tbody>
</table>
The following member is covered by the discordant youngest member to such an extent that this very thick member has as yet no proved outcrop area. The member has therefore been named after the area where its thickest development is seen, namely the Great Plantation.

The Great Plantation Member is mainly sideritic clayey silts, silty clays and sands, reaching a maximum recorded thickness of over 107 metres (350 feet) in Borehole 641 (Section 4, FIG. 6.1.). This borehole however is probably affected by faulting and the adjacent Borehole 642 is considered to be more representative. The Great Plantation Member sequence in Borehole 642 is as follows:

<table>
<thead>
<tr>
<th>Layer Description</th>
<th>Metres</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue-grey silty sandy clay and clayey silt with brownish-yellow, purple and lilac stains as well as mundic stain</td>
<td>13.86 (45' 6&quot;)</td>
</tr>
<tr>
<td>Silty sand</td>
<td>1.07 (3' 6&quot;)</td>
</tr>
<tr>
<td>Sandrock ( siderite-cemented sand )</td>
<td>0.20 (0' 8&quot;)</td>
</tr>
<tr>
<td>Blue-grey sideritic sandy clayey silt with lilac and purple-brown stains</td>
<td>0.71 (2' 4&quot;)</td>
</tr>
<tr>
<td>Silty sand</td>
<td>1.52 (5' 0&quot;)</td>
</tr>
<tr>
<td>Blue-grey sandy clayey silt with blue and lilac stains</td>
<td>2.13 (7' 0&quot;)</td>
</tr>
<tr>
<td>Silty sand</td>
<td>1.52 (5' 0&quot;)</td>
</tr>
<tr>
<td>Grey-blue stained sandy clayey silt</td>
<td>1.52 (5' 0&quot;)</td>
</tr>
<tr>
<td>Silty sand</td>
<td>0.61 (2' 0&quot;)</td>
</tr>
<tr>
<td>Grey-blue sandy gravelly clayey silt with purple and brown stains</td>
<td>2.44 (8' 0&quot;)</td>
</tr>
</tbody>
</table>
Brown silty sand and lignitic material | METRES  
--- | ---
0.76 | (2' 6")

Grey-blue sandy silty clay and clayey silt with brown, lilac and purple stains | 10.82 | (35' 6")

Silty sand | 0.30 | (1' 0")

Blue-grey silty clay | 0.61 | (2' 0")

Brown sandy clay with some lignitic material | 0.30 | (1' 0")

Grey sandy clayey silt | 0.91 | (3' 0")

Brown sandy clay with lignite strands becoming very sandy | 1.52 | (5' 0")

Brown silty sand | 0.61 | (2' 0")

Brown silty clay with lignite bands | 1.14 | (3' 9")

Grey-blue sandy silty clay | 4.34 | (14' 3")

Silty sand | 1.52 | (5' 0")

Grey-blue sandy sometimes gravelly silty clay to clayey silt with considerable blue stain | 6.10 | (20' 0")

Silty sand | 0.61 | (2' 0")

Blue-grey silty sandy clay with purple and brown stain and some siderite spherules | 7.01 | (23' 0")

Silty sand | 2.74 | (9' 0")

Blue-grey silty sandy clay with heavy humic stain | 1.52 | (5' 0")

Brown lignitic clay with lignite bands | 0.61 | (2' 0")

Blue-grey sideritic sandy clayey silt and sandy silty clay with occasional bands of sandrock | 3.96 | (13' 0")

Silty sand | 3.05 | (10' 0")

Blue-grey silty sandy clay with some purple and brown stain | 2.29 | (7' 6")

Brown slightly silty clay | 0.76 | (2' 6")

Silty gravelly sand with occasional clayey areas - base is lignitic material | 4.27 | (14' 0")

Blue-grey clayey silt with bands of sandrock | 0.51 | (1' 8")

Blue-grey silty clay with some purple stain | 0.71 | (2' 4")

Brown silty clay with occasional fine lignite strands | 0.30 | (1' 0")
Blue-grey sandy clayey silt  
Silty sideritic sand  
Brown sandy clay  
Blue-grey silty clay with some silty sand  
Silty sand  
Grey sandy clay

<table>
<thead>
<tr>
<th>METRES</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.30 (1' 0&quot;)</td>
<td></td>
</tr>
<tr>
<td>1.98 (6' 6&quot;)</td>
<td></td>
</tr>
<tr>
<td>1.68 (5' 6&quot;)</td>
<td></td>
</tr>
<tr>
<td>0.91 (3' 0&quot;)</td>
<td></td>
</tr>
<tr>
<td>1.52 (5' 0&quot;)</td>
<td></td>
</tr>
<tr>
<td>1.83 (6' 0&quot;)</td>
<td></td>
</tr>
<tr>
<td><strong>91.07</strong> (299' 0&quot;)</td>
<td></td>
</tr>
</tbody>
</table>

The member, as well as being sideritic, also contains almost invariably traces of felspar on X-Ray Diffraction traces. The Devon & Courtenay Clay Company Limited, boring in the Halford area in 1924 (to the south of the western end of Section 4 — see FIG. 6.2.), located seams of grey-blue clays resting on brown clays and lignite, the total thickness of which is about 15 metres (50 feet). This sequence overlies grey-blue sandy and mottled clay, followed by sand, and is overlain by sands. The dip is 1 in 5 to the north-north-west. This sequence is considered to be part of the Great Plantation Member. Although a German company had worked these clays, prior to the First World War, no further working has taken place since then.

6.10. The youngest member of the Bovey Formation is the Bovey Heath Member which lies discordantly over much of the north-western half of the basin. The thickest section of the member is on the northern half of Bovey Heath where it is about 49 metres (160 feet) thick and the base is some 12 metres (40 feet) below Ordnance Datum. As the base of the member is only some 9 metres (30 feet) above Ordnance Datum on Section 5 (FIG. 6.2.), some 1830 metres (6000 feet) to the south, the dip is extremely low (1 in 87 in the north). In the limited exposures of this member, there is evidence of considerable reworking with muddy, silty,
gravelly sands (often with silty clay pellets) forming the bulk of the sequence. A typical sequence from the northern end of Bovey Heath is as follows:-

<table>
<thead>
<tr>
<th>METRES</th>
<th>Grey and yellow muddy silty gravelly sand</th>
<th>14.94</th>
<th>(49' 0&quot;)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lignitic clayey silty sand</td>
<td>0.30</td>
<td>(1' 0&quot;)</td>
</tr>
<tr>
<td></td>
<td>Grey and yellow muddy silty gravelly sand</td>
<td>7.32</td>
<td>(24' 0&quot;)</td>
</tr>
<tr>
<td></td>
<td>Brown lignitic clay crammed with lignitised plant remains and thin lignite bands</td>
<td>2.44</td>
<td>(8' 0&quot;)</td>
</tr>
<tr>
<td></td>
<td>Grey and yellow muddy silty gravelly sand becoming darker towards the base with occasional clayey areas</td>
<td>11.28</td>
<td>(37' 0&quot;)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>36.28</td>
<td>(119' 0&quot;)</td>
</tr>
</tbody>
</table>

It is possible that this member contains material derived from older Bovey Members which were pushed up along the Western Boundary Fault and which have been subsequently eroded.

6.11. The structure of the Bovey Basin is complex with later faulting superimposed on the complex offlap/overlap relationships of the various members. The best known members, the Southacre and Abbrook Members, on the eastern outcrop, show generally plane dips towards the centre of the basin, varying generally between 1 in 5 and 1 in 8 but increasing occasionally to 1 in 2 (such as the Chudleigh Knighton area). Except in the Ringslade/West Golds area no reverse outcrop of these two members is found. This is probably due to the shift in emphasis of sedimentation before Brimley times, with the western outcrop of the earlier members being buried under the later sediments. The faulting, from the clean cut line of the fault, took place some time after the sediment was consolidated. This is illustrated by Plate 6.1., which shows the Lappathorn Sand faulted against an Abbrook clay and shows the clear cut
line of the fault plane. This Plate also illustrates the general lack of any sedimentary structures in the sand which is invariable in the limited exposures so far seen. Plate 6.2. shows faulting in the Southacre Member, in a lignitic sequence in Southacre Pit.

The faults are generally oblique slip normal faults, downthrow being generally (but not invariably) to the southern and eastern (up-dip) side of the faults. The slip component appears to have moved the down-throw side of many of the faults to the north-west (i.e. a sinistral movement rather than the dextral movement of the Sticklepath Fault System). Only three known faults throw to the down-dip side, and no fault so far seen stops short at an unconformity. This implies that the faults are not subsidence but were the results of later tectonic movements. The throws on the faults (excluding the large fault to the west of Bovey Heath) vary up to 24 metres (80 feet) and generally are in the range 3 metres (10 feet) to 12 metres (40 feet). The hade of the faults are usually in the 40° to 50° range. The main basin can be divided into two parts when considering the directions of faulting. The north-western half, to the north-west of a line from Staplehill on the south-west to Rixey Park on the north-east, in which faulting is parallel to the Sticklepath Fault Trend of north-west/south-east, and the south-eastern half in which the direction is more variable (see FIG. 6.4.). In the extreme south, the faults trend south-west/north-east, gradually swinging to a north/south direction in the Preston Manor (Southacre and White Pit) area. The fault illustrated in Plate 6.1., as well as downthrowing to the dip, is the only fault so far found in the south-eastern half of the basin which has the Sticklepath trend. This fault appears to be truncated by the north/south trending faults which suggests that the faulting in the south-eastern half was later.
Fig. 6.4 Faulting in the Bovey Basin

**Key**
- Dartmoor Granite
- Boundary of the Bovey Beds
- Built up areas
- Thrust
- Faults

Scale 1:50,000
PLATE 6.1.
Faulting at the North End of White Pit.

PLATE 6.2.
Faulting in Southacre Pit.
Although, probably, this fault pattern could be explained by second and third order relationships, on the main Sticklepath trend, the present author considers the pattern in a different light. The earlier Sticklepath trend faults in the north-western half of the basin and the similar trending fault-controlled Decoy 'outlier' probably occurred fairly late in the Tertiary, certainly after sedimentation was complete in the Bovey Basin. Later Alpine movements from the south were possibly deflected to the north-east around the eastern extremities of Dartmoor which would be acting as a stable block. This could have had the effect of pushing the south-eastern part of the main basin towards Haldon and imparting the wrench component on these oblique slip faults. Also this would explain the north-east/south-west trend of the most southerly of the faults. Further to the east, and clear of the eastern bulge of the granite, the trend would return to a north/south direction resulting in the complicated Preston Manor fault system.

It would appear that the faulting is proportional to the degree of boring and working information which is certainly partly true. Often, however, economic exploitation takes place in the areas of greatest faulting because of the repeated outcrops with this type of faulting. The most complex structural area is the Preston Manor area where the greatest exploitation still continues. Other areas have been bored without recording definite faulting which is revealed by sequences missing from the borehole sections. Although numerous other faults probably are as yet unrecorded, FIG. 6.4. is considered to reflect the faulting not only in pattern but also in intensity.
6.12. The age of the Bovey Beds is still not determined. If the Middle Oligocene age of Pengelley, Reid and Chandler is accepted, this only applies to the Brimley Member. A considerable column of strata exists below the Brimley Member, often with intervening unconformities. The unconformities in certain cases may represent considerable periods of time, particularly that which occurs between the Brimley and the Stover and Blatchford Members, when the whole emphasis of sedimentation shifted to the north and west. It is quite possible that a considerable portion of the Bovey Deposit is of Eocene age as has recently been suggested at Petrockstow. Similarly, the overlying strata of the Brimley Member have unconformable relationships. The final member, the Bovey Heath Member, which contains considerable reworked material, rests with complete discordance almost horizontally over the lower members. It could well be that this member represents one of the later Tertiary Periods. The Bovey Basin could contain strata that represent practically the whole of the Tertiary. There is however no substantial evidence for this supposition and, except for statistical pollen analysis, it does not appear likely that there will be a satisfactory answer to this intriguing question.
7. RESULTS AND DISCUSSION OF RESULTS.

7.1. Moisture Content.

The variation in moisture content in the Southacre and Abbrook Members is shown in TABLE 7.1.1. and FIG. 7.1.1. The moisture content appears to vary in a straight line relationship to SiO₂ content of the clays with little apparent change for the small differences in level of sampling points. The siliceous clays have the lowest moisture content (10.8%) and the carbonaceous clays the highest (25.8%). Silica content generally reflects the particle size, the siliceous clays usually being very much coarser than the carbonaceous clays. Because of this finer grain the carbonaceous clays have a much higher surface area with a consequent increase in the surface films of water around each particle; in addition, the packing characteristics of the fine platy kaolinite tends to prevent easy migration of water. The coarser grained quartzitic clayey silts, however, have much less surface area, and the packing characteristics of the more spherical quartz grains would more readily facilitate migration of moisture under overburden pressure. Silica content also to some extent reflects the mineralogy of the material. Obviously, a higher silica content reflects a higher proportion of free quartz and a correspondingly lower kaolinite content. It does not, however, reflect the proportion of mica or mixed layer minerals, which could well have considerable influence on moisture content.

There are a number of factors which can affect moisture content. Among the most important are:

(a) Particle Size
(b) Mineralogy
(c) Overburden Pressure
(d) Time
FIG. 7.2.1. Change in Bulk Density with Increasing Depth of the Parks Seam.

TABLE 7.1.1. Variation of Moisture in the Southacre and Abbrook Members (Levels referred to 1000 feet below O.D.)

<table>
<thead>
<tr>
<th>MEMBER</th>
<th>SiO₂ %</th>
<th>MOISTURE %</th>
<th>LEVEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOUTHACRE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>44.8</td>
<td>23.5</td>
<td>973</td>
</tr>
<tr>
<td></td>
<td>48.2</td>
<td>21.0</td>
<td>971</td>
</tr>
<tr>
<td></td>
<td>47.0</td>
<td>23.0</td>
<td>971</td>
</tr>
<tr>
<td></td>
<td>53.4</td>
<td>17.6</td>
<td>973</td>
</tr>
<tr>
<td></td>
<td>53.0</td>
<td>19.4</td>
<td>970</td>
</tr>
<tr>
<td></td>
<td>46.0</td>
<td>25.8</td>
<td>952</td>
</tr>
<tr>
<td></td>
<td>50.2</td>
<td>17.8</td>
<td>945</td>
</tr>
<tr>
<td></td>
<td>46.0</td>
<td>22.6</td>
<td>945</td>
</tr>
<tr>
<td>ABBROOK</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>60.4</td>
<td>18.4</td>
<td>994</td>
</tr>
<tr>
<td></td>
<td>60.7</td>
<td>19.0</td>
<td>1026</td>
</tr>
<tr>
<td></td>
<td>69.5</td>
<td>15.2</td>
<td>1026</td>
</tr>
<tr>
<td></td>
<td>54.3</td>
<td>18.4</td>
<td>1025</td>
</tr>
<tr>
<td></td>
<td>75.4</td>
<td>10.8</td>
<td>1058</td>
</tr>
<tr>
<td></td>
<td>75.0</td>
<td>11.0</td>
<td>1051</td>
</tr>
</tbody>
</table>
Silica content reflects the particle size, although variations in particle size of free quartz and variation in mineralogy would be expected to give considerable scatter of results. The effect of overburden pressure would be expected to give a lower moisture content with increasing depth (i.e. down dip in the same seam). With the passage of time the older clays would be expected to have a lower moisture content. Inspection of FIG. 7.1.1. appears to indicate that the Abbrook clays (i.e. the older clays) could well have higher moisture contents for equivalent silica content, apparently the reverse of what would be expected. FIG. 7.1.2. was expected to show variation of moisture content in various seams with depth (moisture content is shown on the left of the borehole column and silica content on the right). However, what is evident from FIG. 7.1.2. is that, if such a trend exists, it is not recognisable within the range of depths investigated. Unfortunately, with the present boring programme a greater range will not be possible for some time but further investigation will continue when the opportunity arises.

Comparison between the Stover, Southacre and Abbrook Members shows no apparent dependence of moisture content on depth or time. In fact, some of the highest moisture contents recorded were in the Carbonaceous Seams of the Abbrook Member. This seam has a similar particle size range to the carbonaceous clays of the Southacre Member, yet although the Abbrook Clays are older and deeper they have a slightly higher general moisture content. This phenomenon is undoubtedly due to mineralogical differences, the Abbrook clays being generally composed of more highly disordered kaolinite (see FIG. 7.6.24.) and containing more mixed layer and micaceous minerals than the clays of the Southacre Member.

The conclusion reached is that moisture content primarily depends on lithology and, apparently, depth and time are secondary in effect and cause little if any variation within the range of depth and time investigated.
FIG. 7.12. VARIATION OF MOISTURE WITH DEPTH AND LITHOLOGY.
7.2. **Bulk Density.**

Changes in bulk density (all values are quoted in gm/cc) are small but, as would be expected, there is a trend towards higher values with increasing depth (see FIG. 7.2.1. and TABLE 7.2.1.). The Parks Seam varies from 1.68 at Level 943 to 1.88 at Level 176, a change of 0.20 in 767 feet. The bulk density values registered are on dried samples and involve a loss in weight and probably some shrinkage. As the moisture content of the Parks Seam is in the order of 20%, the true bulk density (ignoring shrinkage) is probably over 2 which is fairly close to the value taken by Fasham (1971).

TABLE 7.2.2. shows that there is not only a variation in bulk density due to depth but also with lithology. Particle size and shape are obviously important when considering kaolinite and quartz, which both have a specific gravity of about 2.65. The two silty clays at 54'6" and 355' illustrate the importance of particle size and shape. The higher of the two samples shows the lowest bulk density (1.56), as would be expected, but the sample some 300 feet further down the borehole shows the highest recorded bulk density of 1.92. Obviously the packing characteristics are very different although the SiO₂ and free quartz proportions are similar. Another important factor is the amount of carbonaceous material present in both colloidal form and otherwise. The three lower samples, although not by any means carbonaceous, contain some carbon and lignitised plant remains which are sufficient to record a lower bulk density in spite of the increasing depth of burial. As with moisture content, bulk density appears to depend more on lithology than depth of burial, although the latter factor has more significance than so far recorded with moisture content. Although the results on bulk density seem to confirm Fasham's calculations, the reduced bulk density of the very carbonaceous clays and lignites which form a considerable proportion of the known sediments in the Bovey Basin could well reduce the 4200-foot estimate of the overall depth of the Bovey Basin.
<table>
<thead>
<tr>
<th>BOREHOLE</th>
<th>DEPTH</th>
<th>LEVEL OF BASE*</th>
<th>BULK DENSITY READINGS ON SELECTED PIECES</th>
<th>MEAN BULK DENSITY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>159</td>
<td>94'0&quot; - 102'0&quot;</td>
<td>943</td>
<td>1.67</td>
<td>1.68</td>
</tr>
<tr>
<td>176</td>
<td>131'0&quot; - 140'0&quot;</td>
<td>902</td>
<td>1.70</td>
<td>1.75</td>
</tr>
<tr>
<td>204</td>
<td>136'6&quot; - 146'0&quot;</td>
<td>885</td>
<td>1.65</td>
<td>1.73</td>
</tr>
<tr>
<td>205</td>
<td>139'0&quot; - 148'6&quot;</td>
<td>885.5</td>
<td>1.73</td>
<td>1.79</td>
</tr>
<tr>
<td>205</td>
<td>140'0&quot; - 148'0&quot;</td>
<td>887</td>
<td>1.75</td>
<td>1.76</td>
</tr>
<tr>
<td>205</td>
<td>220'0&quot; - 234'0&quot;</td>
<td>775</td>
<td>1.71</td>
<td>1.75</td>
</tr>
<tr>
<td>643</td>
<td>822'0&quot; - 826'6&quot;</td>
<td>175</td>
<td>1.91</td>
<td>1.90</td>
</tr>
</tbody>
</table>

*Referred to 1000 feet below O.D.

**TABLE 7.2.1. VARIATION OF BULK DENSITY - PARKS SEAM**

<table>
<thead>
<tr>
<th>BOREHOLE 643</th>
<th>BULK DENSITY READINGS ON SELECTED PIECES</th>
<th>MEAN BULK DENSITY</th>
<th>SIO2 %</th>
<th>FREE QUARTZ %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>54'6&quot; - 57'6&quot;</td>
<td>1.57</td>
<td>1.62</td>
<td>1.58</td>
<td>1.46</td>
</tr>
<tr>
<td>355'0&quot; - 362'0&quot;</td>
<td>1.94</td>
<td>1.94</td>
<td>1.79</td>
<td>1.84</td>
</tr>
<tr>
<td>588'0&quot; - 593'0&quot;</td>
<td>1.84</td>
<td>1.83</td>
<td>1.79</td>
<td>1.87</td>
</tr>
<tr>
<td>604'0&quot; - 610'0&quot;</td>
<td>1.97</td>
<td>1.76</td>
<td>1.94</td>
<td>1.92</td>
</tr>
<tr>
<td>816'0&quot; - 822'0&quot;</td>
<td>1.89</td>
<td>1.88</td>
<td>1.84</td>
<td>1.96</td>
</tr>
</tbody>
</table>

**TABLE 7.2.2. VARIATIONS OF BULK DENSITY - BOREHOLE 643**
7.3. **Particle Size.**

FIG. 4.1. and TABLE 7.3.1. show that the clays generally have two particle size distribution curves. With the addition of a deflocculant, an ultimate curve is obtained. This is not, however, how the clay occurs naturally and a further curve can be obtained by dispersing the material simply by mechanical means. Both curves are reproducible, both within the same sample and within samples from the same horizon. This fact is considered to be the first link in the chain of evidence which indicates that the ball clays were laid down in a flocculated state. When considering sedimentation, the natural curve is of greater importance but, as many samples have a high degree of flocculation, it is not always possible to obtain a 'natural' curve with the Sedigraph and the 'ultimate' analysis has to be interpreted accordingly.

<table>
<thead>
<tr>
<th>Percent less than e.s.d.</th>
<th>Particle Size Distribution of a Carbonaceous Clay from the Abbrock Member.</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 μ</td>
<td>91</td>
</tr>
<tr>
<td>10 μ</td>
<td>83</td>
</tr>
<tr>
<td>5 μ</td>
<td>77</td>
</tr>
<tr>
<td>2 μ</td>
<td>66</td>
</tr>
<tr>
<td>1 μ</td>
<td>57</td>
</tr>
<tr>
<td>0.5μ</td>
<td>40</td>
</tr>
</tbody>
</table>
FIG. 7.3.1. Variation in Particle Size Distribution in a Semi-Carbonaceous Seam of the Southacre Member. The five samples tested were taken vertically from a 3-foot seam, numbered from the base upwards.

FIG. 7.3.1. shows the variation in the ultimate particle size distribution in a Semi-Carbonaceous Seam of the Southacre Member. Within the margin of sampling and experimental error, the particle size distributions of these five samples are virtually identical and show no signs of grading or fining upward.

FIGS. 7.3.2. and 7.3.3., however, do show that variation does occur within a Slightly Carbonaceous Seam of the Abbrook Member. Ten samples taken vertically show a gradual coarsening from the base to midway in the seam, followed by a fining-coarsening-fining upward sequence. This is accentuated in the finer fraction (i.e. less than 0.5 microns).
FIG. 7.3.2. Variation in Particle Size Distribution in a Slightly Carbonaceous Seam of the Abbrook Member. The ten samples were taken vertically from a 6-foot seam, numbered from the base upwards.

FIG. 7.3.3. Variation in Particle Size Distribution in a Slightly Carbonaceous Seam of the Abbrook Member.
FIGS. 7.3.4. and 7.3.5. show even greater variation in a Non-Carbonaceous Low Silica Clay of the Abbrook Member. The middle part of this seam shows a coarsening upwards in all size ranges. The chemical and mineralogical characteristics of each seam proved to be almost identical, showing that there was little change in provenance. The reasons for the variation must therefore be sedimentological and probably due to

(a) variation in degree of flocculation and flocc size

and (b) variation in concentration

or, more likely, to a combination of both. In the case of the slightly carbonaceous clay, the greatest variation occurs in the finest fraction, indicating that the main influence was probably concentration. 'En masse' settling occurs when particles interfere to such an extent that all fine particles are entrained and downward movement of the larger particles and floccs is impeded so that the whole settles without any grading or fining upwards. 'En masse' settling can occur with increasing flocc size or increasing concentration. When concentration or smaller floccs occur, the particles cease to interfere sufficiently to entrain the fine particles. Hence much of the finer fraction is left in suspension until such time as the concentration increases so that all the fine particles (including possibly many 'residual' fine particles left in suspension) are entrained. The resulting 'layer' would be identical in mineralogy but much finer in grain. The variation in the Non-Carbonaceous Seam is more difficult to explain. Probably both degree of flocculation and concentration are responsible. Smaller floccs, relatively further apart, would lead to an increase in the proportion of particles greater than 0.5 microns in the resulting sediment. These larger particles, together with the floccs, settle as a fine silt, entraining a relatively small proportion of the finest particles. The residual suspension of fine particles, with increasing
FIG. 7.3.4. Variation in Particle Size Distribution in a Non-Carbonaceous Low Silica Clay of the Abbrook Member. The nine samples tested were taken vertically from the face of an underground mine, representing a 5'6" section of the seam. The samples are numbered from the base upwards.

FIG. 7.3.5. Variation in Particle Size Distribution in a Non-Carbonaceous Low Silica Clay of the Abbrook Member.
flocculation or concentration, may well contribute to later layers. In this way, variations in particle size could occur, characterised by coarsening upwards and sharp 'fining' with, at times, a rhythmic basis. These characteristics contrast with the more normal 'fining' upwards concept of sedimentation.

FIG. 7.3.6. shows that such variations are not general. Examination of a 5-inch core of carbonaceous clay from the Abbrook Member shows little variation in either ultimate or natural particle size distribution, indicating that there was little change in the provenance, degree of flocculation or concentration of the slurry throughout the deposition of this particular sample. Indeed, inspection of numerous samples from this seam over a wide area reveals little variation showing that there was little change in conditions over a fairly long interval of time.

FIG. 7.3.6. Variation in Particle Size Distribution in a Carbonaceous Clay of the Abbrook Member. Nine samples were tested taken normal to the dip from five inches of HQ core (2½" diameter).
To summarise, the particle size distribution within a seam is usually uniform although, in some non-carbonaceous seams, coarsening upwards and subsequent sharp fining can be recognised.

Particle size distribution curves of typical sediments in the various members are shown in FIGS. 7.3.7. to 7.3.37. (FIGS. 7.3.9. to 7.3.37. are contained in Appendix I).

7.4. **Settling Trials.**

A carbonaceous clay from the Abbrook Member was chosen for the initial trials. This clay has a particle size distribution as shown in FIG. 4.1. and TABLE 7.3.1.

Firstly, the settling characteristics of a deflocculated sample were investigated. The clay was dispersed at 8% solids with the addition of a deflocculant. The cylinder of slurry was shaken and allowed to settle. The results are illustrated in Plates 7.4.1., 7.4.2. and 7.4.3.

After one week's settling, a lighter coloured band appeared at the base, with a black, translucent supernatant appearing at the top. After three weeks' settling (see Plate 7.4.3.), these bands have clarified, the lower light band being about 3% and the 'black' supernatant about 1.5% of the total volume. The 'black' supernatant contains colloidal carbon which remains suspended. A similar settling experiment was started in 1966 and the result after some eight years' settling is shown in Plate 7.4.4.

The light band has hardened and has a darker, thinner band resting on it. The bulk of the cylinder, however, is occupied by a dark brown uniform suspension of colloidal carbon.
Fig. 7.3.7. Particle Size Analysis of the Sole Non-Siliceous Clay of the Bovey Heath Member.

Fig. 7.3.8. Particle Size Analysis of a typical clay from the Great Plantation Member.
PLATE 7.4.1.
Deflocculated 8% Solids
Slurry of an Abbrook
Carbonaceous Clay at
Commencement of Settling.

PLATE 7.4.2.
Deflocculated Slurry After
Settling for One Week.
PLATE 7.4.3.
Deflocculated Slurry After Settling for Three Weeks.

PLATE 7.4.4.
A Carbonaceous Clay After Settling for Eight Years.
The settling of the deflocculated sample shows that, under such conditions, grading of the material takes place. The coarser particles settle initially, followed by the finer particles, giving a banded appearance to the sedimented material at the base of the cylinder. The finely divided colloidal carbon, being of a lower density, remains in suspension and gives the dark colour to the supernatant. The natural sediment, however, contains colloidal carbon but does not have a banded appearance and is further evidence to suggest that the clay in fact was not sedimented in a deflocculated state.

Five further cylinders of slurry at 8% solids were dispersed without addition of a deflocculant. The natural pH of the slurry was measured at 5.6. The other four cylinders were adjusted to pH 4.9, 4.2, 3.5 and 2.1. The cylinders were shaken at 08.45 hours on 5th June 1973 (Plate 7.4.5). Slight differences in the dimensions of the measuring cylinders explain the apparent slight differences in level of the 1000 cc mark from cylinder to cylinder.

After two hours, the slurries had settled as shown in Plate 7.4.6.

The pH 5.6 cylinder shows little change, other than a slight lightening in colour of the top 5 cc, and the development of a darker band at the base. The pH 4.9 tube has developed an indistinct mudline at 880 cc, but with a very cloudy supernatant, and it has also developed a dark band at the base.

The pH 4.2 cylinder has developed a distinct mudline at 770 cc with a cloudy supernatant, and some indistinct banding at the base. The pH 3.5 and pH 2.1 cylinders have developed sharp mudlines at 900 cc, with clear supernatants and homogeneous sediment below the mudlines.
Settling of an 8% Solids Natural Slurry of an Abbbrook Carbonaceous Clay Under Conditions of Varying pH.
After four hours, the mudline has reached 725 cc (pH 4.9), 530 cc (pH 4.2), 655 cc (pH 3.5) and 755 cc (pH 2.1).

After six hours (at 14.45 hours), the pattern has become established. (See Plate 7.4.7.).

The pH 5.6 cylinder shows little change with merely intensification of the dark band at the base. The pH 4.9 cylinder has a more distinct mudline at 565 cc., with a cloudy supernatant beginning to clear at the top. The dark band is established at the base but less distinctly than in the higher pH cylinder. The pH 4.2 cylinder has a distinct mudline at 365 cc and the cloudy supernatant is translucent with a diminishing number of particles held in suspension towards the fluid surface. The base has a thin discrete dark band overlain by a diffuse band of disseminated darker floccs entrained in lighter material. The pH 3.5 and pH 2.1 tubes have mudlines at 520 and 720 cc, both with clear supernatants and homogeneous sediment.

After eight hours (at 16.45 hours), the pattern remains unchanged (Plate 7.4.8.). The pH 4.9, pH 4.2, pH 3.5 and pH 2.1 mudlines have reached 420 cc, 340 cc, 490 cc and 690 cc respectively, the only other change being in the opacity of the pH 4.9 and pH 4.2 supernatants.

By 08.45 hours on 6th June 1973 (after twenty-four hours), the pH 5.6 cylinder has shown some signs of change.

The whole cylinder has become lighter in colour, the dark band at the base has become intensified and the upper 3% has become translucent. The mudlines of the other cylinders have reached 330 cc (pH 4.9), 280 cc (pH 4.2), 410 cc (pH 3.5) and 584 cc (pH 2.1). The supernatant of the pH 4.9 cylinder has become translucent and the upper part has few particles still in suspension. The pH 4.2 supernatant is now clear.
The mudlines continue to fall very slowly, with readings being taken at 28 hours, 31 hours, 32½ hours, 48 hours (Plate 7.4.9.), 52 hours, 56½ hours, 72 hours, 80½ hours, 168 hours and 336 hours. The supernatant of the pH 4.9 cylinder cleared by 32½ hours. At 168 hours, the pH 5.6 tube developed an indistinct mudline at 360 cc, which then fell comparatively rapidly.

The final recordings were made at 10.15 hours on 9th July 1973, over a month after commencement of settling (Plate 7.4.10.).

The pH 5.6 cylinder has an indistinct mudline at approximately 200 cc with a very cloudy supernatant and a distinct dark band at the base. The pH 4.9, pH 4.2, pH 3.5 and pH 2.1 mudlines have reached 160 cc, 150 cc, 230 cc and 260 cc respectively.

When this clay is allowed to settle in a flocculated condition at natural pH, the darkest band develops at the base of the cylinder and the eventual supernatant is clear, indicating that the colloidal carbon is now part of the heaviest and largest of the floccs, which naturally reach the base first. Flocculation is usually accepted as being caused by the attraction of opposite charges. The charge on kaolinite is negative overall but the edges of the crystals have a positive charge (Schofield and Samson, 1954). Hence, floccs are built up in kaolinite by edge to face relationships. Carbon compounds, however, are very variable and positive and negative charges are probably found on different areas of the same particles so that both faces and edges of kaolinite crystals, or other carbon particles with an opposite nett charge, may be attracted to an individual carbon particle. Study of Plates 7.4.5. to 7.4.10. reveals that the lighter carbon particles are now part of the largest floccs which settle fastest.

It has already been shown that banding and grading with fining upwards sequences do not exist in the ball clays, indicating that
Settling of an 8% Solids Natural Slurry of an Abbrook Carbonaceous Clay Under Conditions of Varying pH.
(a) the clays could not have been sedimented in a deflocculated state
and (b) the clays must also have settled 'en masse' or else some form of banding or fining upwards could be recognised.

FIG. 7.4.1. and TABLE 7.4.1. show graphically what is illustrated in Plates 7.4.5. to 7.4.10. The pH 2.1 and pH 3.5 cylinders are settling 'en masse' with a clear supernatant virtually from the outset. The pH 2.4 cylinder settles freely for 6 hours but becomes very slow subsequently as the trapped water can only escape very slowly upwards past the particles which now interfere with each other to a greater extent with the passing of time. Although the pH 4.2 cylinder reaches the smallest final volume, it shows signs of banding and the supernatant is cloudy at the outset. The pH 3.5 cylinder settles 'en masse' with a clear supernatant but, for 6 hours, settlement to half the original volume takes place fairly quickly. During this phase, the large floccs, which must incorporate all the fine particles, are sufficiently far apart to allow free upward passage of water. At the end of this period, hindered settling commences, on a parallel curve to the 4.2 pH cylinder. This suggests that at 8% solids the optimum pH for settling of this Abbrook Carbonaceous Clay slurry is between 3.5 and 4.2. This premise however discounts two facts:

(i) the natural particle size distribution indicates that complete flocculation, such as occurs in the pH 3.5 cylinder, did not occur during the natural sedimentation
and (ii) the natural pH at 8% solids is 5.6, which must reflect the natural sedimentation pH - certainly more neutral than the 3.5 to 4.2 pH suggested.
FIG. 7.4.1  SETTLEMENT OF AN 8% SOLIDS CARBONACEOUS CLAY SLURRY UNDER CONDITIONS OF VARYING pH

<table>
<thead>
<tr>
<th>HOURS</th>
<th>pH 2.1</th>
<th>pH 3.5</th>
<th>pH 4.2</th>
<th>pH 4.9</th>
<th>pH 5.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>900*</td>
<td>900*</td>
<td>770</td>
<td>880</td>
<td>995</td>
</tr>
<tr>
<td>4</td>
<td>755</td>
<td>655</td>
<td>530</td>
<td>725</td>
<td>990</td>
</tr>
<tr>
<td>6</td>
<td>720</td>
<td>520</td>
<td>365</td>
<td>565</td>
<td>990</td>
</tr>
<tr>
<td>8</td>
<td>690</td>
<td>490</td>
<td>340</td>
<td>420</td>
<td>990</td>
</tr>
<tr>
<td>24</td>
<td>584</td>
<td>410</td>
<td>280*</td>
<td>330</td>
<td>985</td>
</tr>
<tr>
<td>28</td>
<td>569</td>
<td>400</td>
<td>270</td>
<td>321</td>
<td>983</td>
</tr>
<tr>
<td>30</td>
<td>560</td>
<td>393</td>
<td>263</td>
<td>320</td>
<td>981</td>
</tr>
<tr>
<td>32½</td>
<td>550</td>
<td>390</td>
<td>260</td>
<td>319*</td>
<td>980</td>
</tr>
<tr>
<td>48</td>
<td>496</td>
<td>360</td>
<td>235</td>
<td>292</td>
<td>970</td>
</tr>
<tr>
<td>52</td>
<td>486</td>
<td>355</td>
<td>231</td>
<td>290</td>
<td>970</td>
</tr>
<tr>
<td>56½</td>
<td>473</td>
<td>350</td>
<td>229</td>
<td>283</td>
<td>969</td>
</tr>
<tr>
<td>72</td>
<td>436</td>
<td>330</td>
<td>212</td>
<td>267</td>
<td>960</td>
</tr>
<tr>
<td>80½</td>
<td>420</td>
<td>320</td>
<td>210</td>
<td>250</td>
<td>959</td>
</tr>
<tr>
<td>168</td>
<td>313</td>
<td>268</td>
<td>179</td>
<td>208</td>
<td>360</td>
</tr>
<tr>
<td>336</td>
<td>277</td>
<td>240</td>
<td>170</td>
<td>179</td>
<td>280</td>
</tr>
</tbody>
</table>

(* Clear supernatant)

TABLE 7.4.1  Settlement of an 8% Solids Carbonaceous Clay Slurry under conditions of varying pH.
Therefore, although flocculation is an important factor, it cannot be the sole mechanism in the sedimentation of these very fine particles of kaolinite.

Settling 'en masse' can also occur as the concentration of particles increases, a factor which is illustrated in Plates 7.4.11 to 7.4.16., TABLE 7.4.2. and FIG. 7.4.2.

<table>
<thead>
<tr>
<th>HOURS</th>
<th>15% Solids</th>
<th>20% Solids</th>
<th>25% Solids</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>870</td>
<td>920</td>
<td>990</td>
</tr>
<tr>
<td>3</td>
<td>803</td>
<td>870</td>
<td>980</td>
</tr>
<tr>
<td>4</td>
<td>740</td>
<td>821</td>
<td>973</td>
</tr>
<tr>
<td>6</td>
<td>610</td>
<td>729</td>
<td>960</td>
</tr>
<tr>
<td>7½</td>
<td>512</td>
<td>650</td>
<td>948</td>
</tr>
<tr>
<td>7½</td>
<td>378</td>
<td>478</td>
<td>787</td>
</tr>
<tr>
<td>7½</td>
<td>372</td>
<td>472</td>
<td>780</td>
</tr>
<tr>
<td>7½</td>
<td>369</td>
<td>409</td>
<td>775</td>
</tr>
<tr>
<td>9½</td>
<td>359</td>
<td>459</td>
<td>756</td>
</tr>
<tr>
<td>10½</td>
<td>350</td>
<td>450</td>
<td>748</td>
</tr>
<tr>
<td>11½</td>
<td>340</td>
<td>440</td>
<td>730</td>
</tr>
<tr>
<td>12½</td>
<td>339</td>
<td>436</td>
<td>720</td>
</tr>
<tr>
<td>14½</td>
<td>330</td>
<td>427</td>
<td>702</td>
</tr>
<tr>
<td>23½</td>
<td>300</td>
<td>390</td>
<td>629</td>
</tr>
<tr>
<td>45½</td>
<td>268</td>
<td>350</td>
<td>519</td>
</tr>
</tbody>
</table>

**TABLE 7.4.2.** Settlement of a Carbonaceous Clay Slurry under conditions of varying concentration.

At the natural level of flocculation only the 25% solids cylinder shows a clear supernatant and an absence of banding. Both the 15% solids and the 20% solids cylinders have fine particles left in suspension initially and both show evidence of banding at the base. FIG. 7.4.2. shows that the 25% solids cylinder is settling 'en masse' with no free settling, unlike the other two cylinders. When hindered settling commences, the three curves are roughly parallel.
PLATE 7.4.11. After Three Hours.

PLATE 7.4.12. After Six Hours.

PLATE 7.4.13. After Three Days.

Settling of a Natural Slurry of an Abbrook Carbonaceous Clay Under Conditions of Varying Concentration.
Settling of a Natural Slurry of an Abbrook Carbonaceous Clay Under Conditions of Varying Concentration.
FIG. 7.4.2. Settling of a Carbonaceous Clay Slurry Under Conditions of Varying Concentration.

FIG. 7.4.3. Increase in Concentration with Time during Settlement of a 25% Solids Carbonaceous Clay Slurry.

FIG. 7.4.4. Variation of pH with Concentration of a Carbonaceous Clay Slurry.
The sedimentation volume of the 25% solids cylinder, however, is much larger after nineteen days than the other two but reference to FIG. 7.4.3. shows that, after this period of time, the sediment below the mudline has reached nearly 50% solids. A metre of turbid water at this concentration would produce, in three weeks, half a metre of hydro-plastic sediment and fairly clear water. Evaporation would probably take place and possibly eventual desiccation, although it is more likely that the next flood of turbid water replenished the shallow lake before actual desiccation could occur, as desiccation cracks are apparently rare. As the concentration of the slurry increased, the pH dropped slightly (see FIG. 7.4.4.) to 5.3 at 25% solids.

These experiments suggest that the Carbonaceous Clays of the Abbrook Member were sedimented from a turbid slurry at 20% to 25% solids (or more) in a partially flocculated condition, at a pH of 5.3.

A Siliceous Clay from the Abbrook Member was investigated next. The ultimate particle size distribution shows this clay to be very much coarser than the Carbonaceous Clay from the Abbrook Member. This particle size distribution is shown in FIG. 7.4.5. and TABLE 7.4.3. Pedantically, the true description of this sediment would be a very clayey silt, the material being only 48.5% less than 2 microns e.s.d. The natural particle size curve indicated a condition of complete flocculation.

The natural pH of the slurry at 8% solids proved to be 6.7. Four other cylinders were mixed and pH values adjusted to 3.1, 4.0, 4.8 and 5.3 respectively. All five cylinders were shaken up and allowed to settle. The results are shown in Plates 7.4.17. to 7.4.22., TABLE 7.4.4. and FIG. 7.4.6. After one hour, the five mudlines had reached 741, 780, 762, 778 and 860 for 3.1 to 6.7 pH cylinders respectively. The supernatants were clear from the outset and no
Fig. 7.4.4. Settlement of an 8% Solids Siliceous Clay Slurry under Conditions of Varying pH.

The supernatants of all the cylinders were clear from the outset.

TABLE 7.4.4.
Settlement of an 8% Solids Siliceous Clay Slurry under Conditions of Varying pH. The supernatants of all the cylinders were clear from the outset.

<table>
<thead>
<tr>
<th>Hours</th>
<th>pH 3.1</th>
<th>pH 4.0</th>
<th>pH 4.8</th>
<th>pH 5.3</th>
<th>pH 6.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>741</td>
<td>780</td>
<td>762</td>
<td>778</td>
<td>860</td>
</tr>
<tr>
<td>4</td>
<td>21%</td>
<td>542</td>
<td>560</td>
<td>531</td>
<td>609</td>
</tr>
<tr>
<td>6</td>
<td>27/6</td>
<td>473</td>
<td>518</td>
<td>540</td>
<td></td>
</tr>
<tr>
<td>4/542</td>
<td>400</td>
<td>499</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4/700</td>
<td>520</td>
<td>598</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7/00</td>
<td>504</td>
<td>599</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4/490</td>
<td>362</td>
<td>630</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4/300</td>
<td>339</td>
<td>460</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5/860</td>
<td>330</td>
<td>450</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7/362</td>
<td>381</td>
<td>469</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8/778</td>
<td>378</td>
<td>400</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10/268</td>
<td>379</td>
<td>459</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 7.4.5. Equivalent Spherical Diameter, Microns.

(1) It is not possible to obtain a natural size distribution at 8% solids.

Ultimate Particle Size Distribution of a Silicious Clay from the Abbrook Member.

Percent Loss than 200 a.s.d.

<table>
<thead>
<tr>
<th>Ultimate</th>
<th>83</th>
<th>13</th>
<th>24</th>
<th>48.5</th>
<th>2.1</th>
<th>42.1</th>
</tr>
</thead>
</table>

TABLE 7.4.3. Ultimate Particle Size Distribution of a Silicious Clay from the Abbrook Member.
Settling of an 8% Solids Natural Slurry of an Abbrook Member Siliceous Clay Under Conditions of Varying pH.
Settling of an 8% Solids Natural Slurry of an Abbrook Member Siliceous Clay Under Conditions of Varying pH.
banding has developed in any of the cylinders. After two hours, the levels had reached 540, 560, 531, 540 and 599 respectively. This pattern continued until, after just over three days, the levels had reached 268, 280, 264, 274 and 307 respectively. FIG. 7.4.6. shows that free settling continued for some four hours, after which hindered settling commenced. As the supernatant was clear, all the particles must be taken up in floccs which, with decreasing pH, would probably start to agglomerate also, thus effectively increasing the particle size. This pattern is evident until the pH 4.0 and pH 3.1 cylinders are considered when, because of greater interference between particles, the process is marginally slower. The pH 3.1 cylinder, however, is marginally faster than the pH 4.0 cylinder, which may be due to the onset of syneresis but is more likely to be due to experimental error. After three days' settling, a metre of this slurry at a concentration of 8% solids would produce 31 cms of sediment at about 26% solids, which would of course still be a quasi-liquid form. Another three weeks or so would obviously reduce the thickness of the sediment but would certainly change its nature to 'hydro-plastic' in which form it is unlikely to be much disturbed by the next flood of slurry.

The reason for large floccs being built around quartz grains is obscure. The charge on quartz is negative and similar to that of kaolinite. Dollimore and Horridge (1973) have shown that, at pH 5.8, the positively charged edges of the kaolinite revert to a negative charge so that kaolinite floccs with edge to face relationships do not occur at higher pH. As the natural pH of the Siliceous Clay slurry is 6.7, the attraction of positively charged edges of kaolinite crystals to the negatively charged quartz cannot be invoked. However, the large kaolinite-quartz floccs are an observed fact and, in part, explain the tremendous range in grain size observed in the sands, clayey silts and some of the clays.
Conditions during the settlement of the Siliceous Clay must have been different from those during sedimentation of the Carbonaceous Clay. The standing water in which the latter settled was probably comparatively shallow with outwash fans on one side, producing unsorted silty sands, and a backswamp on the other, collecting the floating vegetation to form lignites. The Siliceous Clay is more likely to have formed in a deeper lake in which settlement took place in the form of large floccs which, although formed of clay particles, would have settled as silts or even sands. Unlike the Carbonaceous Clay, high concentration is not necessary but the absence of any animal fossils suggests that the lake was turbid and being continually charged with sediment. However, although all the particles in the present sediment are contained in floccs, there is no reason to suppose that many fine particles may not have remained in suspension during the original sedimentation, thus preventing establishment of animal life in the lake. This residual suspension, with possible lowering of the pH causing kaolinite flocculation, might reach sufficient concentration to settle and form seams of less siliceous clay, possibly on a rhythmic basis.

The settling characteristics of these Low Silica Non-Carbonaceous Clays of the Abbrook Member were also investigated. The ultimate particle size distribution curves (FIG. 7.4.7 and TABLE 7.4.5.) show this clay to be nearly as fine grained as the Carbonaceous Clay but containing a greater proportion of particles between 1 micron and 2 microns (13.5%) than the latter (8%). The natural particle size distribution curves however show marked differences. In the case of the Low Silica Non-Carbonaceous Clay, the ultimate and natural curves (FIG. 7.4.7.) are much wider apart than those of the Carbonaceous Clay (FIG. 4.1. and FIG. 7.3.6.). Comparison of TABLE 7.3.1. and TABLE 7.4.5. confirms that the degree of natural flocculation in the case of the Low Silica Non-Carbonaceous Clay
TABLE 7.4.6. Settlement of an 8% Solids Low Silica Non-Carbonaceous Clay Slurry under Conditions of Varying pH.

<table>
<thead>
<tr>
<th>HOURS</th>
<th>pH 3.3</th>
<th>pH 4.1</th>
<th>pH 4.5</th>
<th>pH 5.0</th>
<th>pH 5.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>½</td>
<td>931*</td>
<td>920</td>
<td>912</td>
<td>920</td>
<td>910</td>
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<tr>
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<td>440</td>
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<tr>
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<td>424</td>
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<tr>
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<td>383</td>
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<tr>
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<td>269</td>
<td>274</td>
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<tr>
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<td>222</td>
<td>220*</td>
<td>220</td>
</tr>
<tr>
<td>81</td>
<td>220</td>
<td>220</td>
<td>220</td>
<td>219</td>
<td>219</td>
</tr>
</tbody>
</table>

*Time at which supernatant becomes clear.

**TABLE 7.4.5.** Particle Size Distribution of a Low Silica Non-Carbonaceous Clay from the Abbrook Member.

**FIG. 7.4.8.** Settlement of an 8% Solids Low Silica Non-Carbonaceous Clay Slurry under Conditions of Varying pH.

(C = pH 3.3, A = pH 5.7. Curves for pH 4.1, 4.5 and 5.0 lie mainly between these two curves).
was very much greater than that shown by the Carbonaceous Clay and that these larger flocos contained a greater proportion of particles in the 1 micron to 2 microns range.

The natural pH of an 8% solids slurry of Low Silica Non-Carbonaceous Clay proved to be 5.7 and five cylinders were prepared at 5.7, 5.0, 4.5, 4.1 and 3.3 pH. The resulting settling pattern is shown in TABLE 7.4.6. and FIG. 7.4.8. The five settlement curves are virtually coincident on the scale used, the only apparent differences being in the nature of the supernatants. The supernatant of the pH 5.7 cylinder remained cloudy throughout the 81 hours of the experiment. The pH 5.0 supernatant cleared between 57 and 72 hours, the pH 4.5 between 3½ and 5½ hours, the pH 4.1 at 2½ to 3 hours and the pH 3.3 supernatant was clear from the outset. This indicates that, although large flocos are present at the natural pH, the free fine particles are not being entrained. The uniform colour of the particles in this clay prevented recognition of an obvious colour banding at the base, although variations in 'shade' and some faint layering could be recognised in the higher pH cylinders. Free settling took place for 3 hours at the natural pH, when the level of the mudline had reached 440 which represents a slurry density of 1.115 or 18.7% solids. However, many particles were held in suspension above the mudline so that the true solids content is somewhat less. (The basis for the calculation of slurry density, percent solids and concentration below the mudline is described in Appendix II). The pH 3.3 column settles freely for 2 hours, reaching a level of 473, which represents a slurry density of 1.108 or 17.5% solids, in this case with a clear supernatant. The other three columns lie between these two extremes. When hindered settlement commences, the five curves are virtually coincident, with sedimentation volumes at 81 hours of 219 to 220 (1.225 density or 36.4% solids).
The natural pH, however, is 5.7 and flocculation is not complete so, for 'en masse' settling with the free fine particles being entrained by settlement of large floccs, the concentration of the natural slurry must have been higher than 8% solids. The degree of flocculation, however, is much greater than that of the Carbonaceous Clay so concentrations of 25% solids would certainly not be required to settle the Low Silica Non-Carbonaceous Clay. This clay, although not dissimilar to the Carbonaceous Clay in ultimate particle size, is 7% to 8% higher in silica content and virtually free from fine carbon. The free silica must be in the form of very fine quartz, some of which must be in the clay grade (perhaps accounting for the increase in particles between 1 micron and 2 microns). As in the Siliceous Clay already described, the quartz is having a great effect on the degree of flocculation, which would allow this fine clay to settle as a silt, but perhaps leaving many fine particles still in suspension. It is interesting to note that this particular seam is the one which presents the greatest variation in particle size within the seam.

All the samples so far investigated have been from the Abbrook Member. The final settling trials were therefore made on a Very Carbonaceous Clay from the Southacre Member. Unfortunately, before a particle size distribution curve could be made, the original sample used in the settling trials was mislaid so the seam had to be re-sampled, unfortunately from a slightly different area owing to the advance of the working faces. The particle size distribution shown in FIG. 7.4.9. and TABLE 7.4.7. can therefore only be regarded as similar to that expected from the Very Carbonaceous Clay used in the settling trials.

The particle size distribution indicates that this is one of the finest clays so far investigated, being 60% less than 0.5 microns e.s.d. A natural particle size curve at 8% solids shows a higher degree of flocculation than could be evaluated by the Sedigraph 5000 but it also
showed that flocculation was not complete (i.e. all the fine particles were not taken up in the floccs).

The natural pH of the material at 8% solids proved to be 5.7, and four other cylinders at pH 3.2, pH 3.7, pH 4.5 and pH 5.0 were made up. The results of this settling trial are shown in TABLE 7.4.8. and FIG. 7.4.10. The pH 5.7 cylinder developed a mudline which dropped 17 ccs in 52½ hours and then developed a secondary indistinct mudline after 5 days. The pH 5.0 cylinder developed a mudline which fell 60 ccs in 32½ hours, and then developed a secondary mudline at a much lower level, leaving the original mudline within a cloudy supernatant.
**TABLE 7.4.8.** Settlement of an 8% Solids Very Carbonaceous Clay Slurry from the Southacre Member under Conditions of Varying pH.

*Time at which supernatant became clear. The pH 4.5, pH 5.0 and pH 5.7 cylinders all developed dark bands at base.*

**FIG. 7.4.10.** Settlement of an 8% Solids Very Carbonaceous Clay Slurry under Conditions of Varying pH.
The other three showed free settling for 5 to 7 hours, followed by hindered settling, with the smallest sedimentation volume at pH 4.5. The supernatant of the pH 4.5 cylinder was clear after 48 hours, the pH 3.7 cylinder after 24 hours and the pH 3.2 cylinder from the outset.

The sample tested obviously was not flocculated to the same degree as the sample on which a particle size distribution was carried out. The settling trials indicate that this clay must have settled under conditions of much higher concentration than 8% solids, a fact which is confirmed by the presence of plant debris, such as small twigs, seeds and leaves, which must have been entrained with the finer particles.

The settling trials indicated generally that:

(i) flocculation is an important mechanism in the sedimentation of the ball clays

(ii) there are three main influences on flocculation:
(a) the presence of fine carbon
(b) the presence of fine silica
(c) pH

(iii) the concentration of the slurry from which the ball clays settled is another major factor.

7.5. **Chemistry.**

The chemical analyses of clays, although of fundamental use in correlation and as reflections of other features, have little significance compared to mineralogy and particle size. Silica, alumina and alkali content together with loss on ignition all reflect the mineralogy and presence of carbon. As such, most seams have characteristic analyses which give useful information both for correlation and quality control purposes.
Two chemical properties however have some significance in the sedimentology of the clays, these being TiO\textsubscript{2} and Fe\textsubscript{2}O\textsubscript{3}.

The TiO\textsubscript{2} of the ball clay varies from 0.4\% to 1.9\%, although isolated examples have been recorded outside this range and most samples fall in the range 0.7\% and 1.8\%. The TiO\textsubscript{2} content has, of recent years, been one of the flimsy arguments against a Dartmoor provenance for the ball clays, the TiO\textsubscript{2} content of Dartmoor Granite being generally less than 0.3\%.

On X-Ray Diffraction traces, TiO\textsubscript{2} almost invariably shows peaks typical of anatase which is generally accepted as being authigenic in nature. FIG. 7.5.1. confirms a fact first noticed by Scott (1929) which is that the TiO\textsubscript{2} content increases with increasing SiO\textsubscript{2}. The lowest TiO\textsubscript{2} recordings (0.3\% to 0.5\%) were seen in the low silica clays of the Southacre Member. The distribution of TiO\textsubscript{2} within the various members does not conform to any other general pattern than that of variation of SiO\textsubscript{2}. The inevitable conclusion that can be drawn from this fact is that the anatase is authigenic on the free quartz and that the large amount of scatter at the high silica end of the scale is a particle size effect. The coarser sandy silts would have less surface area than the fine quartz silts of equivalent SiO\textsubscript{2} content and would have less area available for the authigenic growth of anatase.

The provenance of the TiO\textsubscript{2} however remains obscure. The sub-hedral nature of the quartz grains makes it difficult to assume any other provenance than Dartmoor, yet the constant presence of anatase apparently suggests a dual provenance for the sediment. The present author considers it surprising that a dual provenance of such consistent balance would have existed for such a long period of time.
FIG. 7.5.1. VARIATION OF TiO$_2$ CONTENT AGAINST SiO$_2$ CONTENT

FIG. 7.5.2. VARIATION OF Fe$_2$O$_3$ CONTENT AGAINST SiO$_2$ CONTENT
TiO₂ in the Dartmoor Granite probably exists in rutile and ilmenite associated with biotite and in xenolithic inclusions in the granite. Could the weathering of such a material, together with residual enrichment, provide a TiO₂ content in the ball clays which is generally five times that recorded in the Dartmoor Granite?

Fe₂O₃ content of the ball clays shows the opposite trend to TiO₂ in that, with decreasing SiO₂, there is increasing Fe₂O₃ content. (See FIG. 7.5.2.). The general range in Fe₂O₃ is 0.7% to 1.7%, higher values generally being sideritic with recorded values of over 5.0% in some cases. The presence of mundic (marcasite), usually as nodules and weird growths, has surprisingly little effect on the chemical analyses, due mainly to selective sampling, whereas the often fine grained siderite is invariably included.

The trend of decreasing Fe₂O₃ with increasing silica indicates that iron is contained within the kaolinite lattice so that, to some extent, increasing iron indicates increasing 'clay' content. FIG. 7.5.2. also indicates a change with time. Each member can be recognised as a 'blurred' trend on the diagram, with apparently increasing Fe₂O₃ content with the passing of time. The Abbrook Member shows the least 'blurred' trend and also the lowest Fe₂O₃ content. The Southacre Member is also generally very low but also shows the greatest scatter of results, as would be expected in a member with three separate facies. Progressively the Twinyeo, Stover, Brimley, Heathfield, Great Plantation and Bovey Heath Members show increasing iron.

For example, at an SiO₂ content of 70%, the Abbrook Member shows generally an Fe₂O₃ content of 0.8%, the Stover Member 1.0% and the Brimley Member 1.2%. In view of these facts, it is not surprising therefore to find that the Abbrook and Southacre Members are commercially the most important members.
The reason for this apparent increase with time is most likely to be changes in provenance, indicating that, as the Dartmoor Granite was being lowered, the weathering material was becoming richer in iron or, possibly, that a greater degree of isomorphous substitution had taken place. It is, however, strange that the Abbrook Member should have the lower iron contents since it contains the most disordered kaolinite and, generally, the greatest incidence of interstratified mineral and therefore would be expected to contain the largest proportion of material of other than granitic origin.

7.6. Mineralogy.

The Bovey Heath Member consists mainly of gravelly, silty, muddy sands with a single seam of often lignitic clay towards the base. An X-Ray Diffraction trace of this latter clay is shown in FIG. 7.6.1. This trace shows large amounts of kaolinite with a Crystallinity Index of 0.33, quartz, mica and some interstratified mineral. The particle size distribution (FIG. 7.3.7.) shows this clay to be silty, although from the chemical analysis much of the fine silt is kaolinite.

The underlying Great Plantation Member is generally very sandy and often sideritic. An X-Ray Diffraction trace of a typical clay is shown in FIG. 7.6.2. (Appendix III). This material is comparatively low in kaolinite, with a Crystallinity Index of 0.35, high in quartz and mica, and contains felspar and anatase. This material would be described as a very silty clay (FIG. 7.3.8.). FIG. 7.6.2. (Appendix III) shows a sandrock, with typical siderite peaks, tourmaline, felspar, mica and kaolinite together with a large quartz content. FIG. 7.6.4. (Appendix III) is an X-Ray Diffraction trace of a sideritic clay. This also shows typical siderite peaks, as well as tourmaline, felspar, mica, anatase, a high quartz content and kaolinite with a Crystallinity Index of 0.33. FIG. 7.3.9. (Appendix I) shows this material to be a very clayey silt.
All further particle size distributions (FIG. 7.3.10. to FIG. 7.3.35.) can be found in Appendix I, and all X-Ray Diffraction traces (FIG. 7.6.5. to FIG. 7.6.30.) in Appendix III.

The Heathfield Member typically shows kaolinite of Crystallinity Index 0.29, medium quartz, high mica, felspar, anatase and some interstratified mineral. The particle size distribution (FIG. 7.3.10.) shows this sediment to be a silty clay, although many of the particles in the silt grade are probably kaolinite.

A typical clay from the Brimley Member (FIG. 7.6.6.) shows kaolinite of Crystallinity Index 0.31, high mica and quartz, felspar and anatase. This is a much finer clay than any found in the overlying members (FIG. 7.3.11.).

The Stover Member generally tends to be very siliceous. FIG. 7.6.7. is an X-Ray Diffraction trace of a silty clay, showing a disordered kaolinite (Crystallinity Index 0.16), high quartz and mica, tourmaline, felspar and anatase and signs of interstratified mineral. This sediment is surprisingly fine for a siliceous clay (FIG. 7.3.12.).

The only low silica clay found in the Stover Member, shows the kaolinite to be much better ordered (Crystallinity Index 0.40), with only small amounts of both quartz and mica, with no sign of felspar or anatase, but a tourmaline peak at 22° 028. Although this sediment is composed dominantly of clay mineral (i.e. kaolinite), there is only 46% of the particles (FIG. 7.3.13) which fall within the clay grade (less than 2 microns). This fact illustrates the problems of megascopic description of a material containing either clay mineral in the silt grade which cannot be detected by even the most sensitive teeth, or fine particulate quartz, some of which may be in the clay grade but is more readily detected. Hence, the former material is designated a low silica clay whilst the latter is described as very silty clay or even
a clayey silt whilst, upon particle size distribution, both descriptions are not completely accurate. The correct description of the low silica clay should be a 'clayey kaolinite silt'.

A more typical clay from the Stover Member is shown in FIG. 7.6.9. The kaolinite is disordered (Crystallinity Index 0.18), with a moderate quartz content, low mica with signs of felspar and anatase. FIG. 7.3.14. shows this clay to be fairly fine.

The Twinyeo Member is mainly a lignitic member with mainly brown silty clays, very silty clays and carbonaceous clays, with one horizon of low silica sideritic clay similar to Parks.

FIG. 7.6.10. depicts an X-Ray Diffraction trace of a brown silty clay, which contains medium disordered kaolinite (Crystallinity Index 0.38), quartz, mica, felspar, tourmaline and anatase. FIG. 7.3.15. shows that the material is not a silty clay but an extremely clayey silt.

An X-Ray Diffraction trace of the low silica sideritic clay is shown in FIG. 7.6.11. This indicates well ordered kaolinite (Crystallinity Index 0.73), siderite, mica, quartz and possibly felspar. Because of quite large particles of siderite, this material is usually described as a sandy clay on megascopical inspection. The particle size curve (FIG. 7.3.16.) shows this to be a silt and the X-Ray Diffraction traces and chemical analysis show it to be a kaolinite silt.

More typically, many of the clays in the Twinyeo Member are carbonaceous. FIG. 7.6.12. shows such clays to contain medium disordered kaolinite (Crystallinity Index 0.31), quartz, mica and felspar. This clay proved to be very fine grained (FIG. 7.3.17.). The very silty clay (FIG. 7.6.13.) contains medium disordered kaolinite (Crystallinity Index 0.31), high quartz and mica, tourmaline, anatase and felspar and would be described as an extremely silty clay or an extremely clayey silt (49.5% less than 2 microns e.s.d. in FIG. 7.3.18.).
The Southacre Member is more complicated in that it contains several different facies with consequent variation in mineralogy and particle size. FIG. 7.6.14. depicts a typical medium ordered kaolinite (Crystallinity Index 0.48) from the clay facies. This clay also contains small amounts of mica and quartz with some feldspar. Particle size distribution curves (FIG. 7.3.19.) show this clay to be comparatively coarse, with many kaolinite particles in the silt grade. FIG. 7.6.15. shows a typical well ordered kaolinite from the Clay Facies. The Crystallinity Index for the kaolinite in this sample is 0.46, less than the previous trace, yet the two triads between 350 and 450 2θ indicate a better crystallinity than the previous trace. These two triads are considered to be a better indication than the Hinckley Crystallinity Index but they cannot be quantified. FIG. 7.6.15. also shows less quartz and mica and the possible presence of some interstratified material. This clay, although finer than the previous sample (FIG. 7.3.20.), still obviously contains many kaolinite particles in the silt grade.

One of the few marker seams in the whole of the Bovey Basin is the Parks Seam. At the northern end of the basin (FIG. 7.6.16.) the Parks is composed of well ordered kaolinite (Crystallinity Index 0.76), low mica and quartz, siderite and possibly a trace of tourmaline. Particle size distribution of this material shows it to be a clayey kaolinite silt (FIG. 7.3.21.). In the type area (FIG. 7.6.17.) Parks shows a kaolinite Crystallinity Index of 0.79, low mica and quartz with siderite. FIG. 7.3.22. shows this material to be finer than Parks further to the north, although it would still be classified as a very clayey kaolinite silt.

Clays from the Lignitic Facies show more mica and are generally finer grained and slightly more disordered than those from the Clay Facies further to the north.
A silty clay from the upper part of the Lignitic Facies (FIG. 7.6.18.) shows medium ordered kaolinite (Crystallinity Index 0.41), mica, quartz, felspar and a trace of anatase, and is fine grained (FIG. 7.3.23.). A slightly silty clay (FIG. 7.6.19 and FIG. 7.3.24.) shows kaolinite with a Crystallinity Index of 0.43, mica, quartz, felspar, anatase and possibly tourmaline. The quartz content is less than in the previous sample yet, although fairly fine, this clay is coarser and therefore more silty than the previous sample. This illustrates how subjective megascopic descriptions of the sediments of the Bovey Basin are - the descriptions applied depending, to a great extent, on whether the interest of the observer is in clay, sand or lignite.

A carbonaceous clay from the Lignitic Facies shows a similar mineral assemblage (FIG. 7.6.20.). The kaolinite has a Crystallinity Index of 0.42 and moderate quantities of quartz and mica are present together with some anatase and possibly some interstratified mineral. This is the finest clay so far encountered (FIG. 7.3.25.), being 81.5% less than 2 microns e.s.d.

The Sandy Facies of the Southacre Member only rarely contains material which is classified on megascopic inspection as clay. One of these seams is shown in FIG. 7.6.21. and contains well ordered kaolinite (Crystallinity Index 0.61), mica, quartz, felspar and possibly some tourmaline. FIG. 7.3.26. shows this sediment to be an extremely silty clay although, obviously, many of the silt grade particles are composed of kaolinite.

There is an apparent decrease in both crystallinity and particle size from north to south in the Southacre Member, even within one facies. The Chudleigh Knighton area is at the northern end of the Clay Facies and is non-carbonaceous, unlike the southern end. These
clays typically contain well ordered kaolinite (Crystallinity Index 0.58 on FIG. 7.6.22.) and very low mica and quartz. They are also fairly coarse, coming under the heading of clayey kaolinite silts (FIG. 7.3.27.). These Chudleigh Knighton clays are the nearest ball clays to a refined china clay, whose excellent fired colour, low strength and low plasticity these clays emulate. These clays are used for different commercial purposes than the more carbonaceous, finer, more plastic clays further to the south in the Southacre Member.

The Abbrook Member is characterised generally by disordered kaolinite, fine grain size and the presence of interstratified mineral. A seam described as slightly silty semi-carbonaceous clay is shown in FIG. 7.6.23. It contains a disordered kaolinite (Crystallinity Index 0.18), mica, quartz, felspar, anatase and a recognisable quantity of interstratified mineral. It is also a very fine clay being 78.5% less than 2 microns e.s.d. (FIG. 7.3.28.).

The carbonaceous clay seam, on which many of the experiments described in this thesis took place, gives an X-Ray Diffraction trace as shown in FIG. 7.6.24. It contains disordered kaolinite (Crystallinity Index 0.23), mica, quartz, felspar and interstratified mineral. This clay is also one of the finest Bovey ball clays, being 91.5% less than 2 microns e.s.d. (FIG. 7.3.29.).

A slightly silty non-carbonaceous clay (FIG. 7.6.25.) shows disordered kaolinite (Crystallinity Index 0.15), mica, quartz, felspar, tourmaline and interstratified mineral. This clay is not as fine grained as the more carbonaceous clays, being 68% less than 2 microns e.s.d. (FIG. 7.3.30.).

Many of the Abbrook seams are siliceous. A medium silica clay (60-64%) is shown in FIG. 7.6.26., and contains disordered kaolinite (Crystallinity Index 0.19), high mica and quartz, felspar, anatase and
interstratified mineral. Particle size analysis (FIG. 7.3.31.) shows this clay to be comparatively fine (74% less than 2 microns e.s.d.).

A more siliceous clay (66-68%) is shown in FIG. 7.6.23. and FIG. 7.3.32. This extremely silty clay contains disordered kaolinite (Crystallinity Index 0.26), mica, high quartz, tourmaline, felspar, anatase and a trace of interstratified mineral. A very siliceous seam (70-72% SiO₂) is shown in FIG. 7.6.28. and FIG. 7.3.33. This clayey silt contains disordered kaolinite (Crystallinity Index 0.26), high quartz, high mica, tourmaline, anatase, felspar and interstratified mineral. An extremely siliceous seam (76% SiO₂) is shown in FIG. 7.6.29. and FIG. 7.3.34. This clayey silt contains disordered kaolinite (Crystallinity Index 0.20), high quartz, mica, tourmaline, anatase, felspar and interstratified mineral.

The Lappathorn Member mainly consists of mottled silty clays, sands and occasional silty clays. A seam of what appeared to be a clayey silt on silica content was subjected to X-Ray Diffraction (FIG. 7.6.30.) and proved to contain very disordered kaolinite (Crystallinity Index could not be measured) in comparatively small amounts, mica, much quartz, tourmaline, felspar, anatase, interstratified mineral and an iron mineral (probably haematite). FIG. 7.3.35. shows the seam to be much finer than anticipated, being 55% less than 2 microns e.s.d. Many of the quartz particles must therefore be in the clay grade.

From the foregoing information, it is obvious that there is a considerable variation in the Hinckley Crystallinity Index from member to member, with values as low as 0.15 in the Abbrook and Stover Members and values as high as 0.79 in the Parks Seam, with generally high values in the Southacre Member and also in a single seam of well ordered kaolinite in the Twinyeo Member.

Crystallinity can depend on a number of factors:
(i) Provenance - derivation of kaolinite.
(a) proportion of hydrothermal kaolin
(b) proportion of weathering felspar from Dartmoor Granite
(c) proportion of kaolinite derived from the weathering of other country rocks.

(ii) Transport.

(iii) Environment of sedimentation (e.g. leaching).

The erosion and redeposition of hydrothermal kaolins would produce kaolinite of high crystallinity. This premise is based on the evidence presented by modern hydrothermal kaolins. Whether felspar weathering from the granite would produce high crystallinity, intermediate crystallinity or poor crystallinity is obscure. Kaolinite derived from the weathering of country rock would be expected to exhibit poor crystallinity and would also be expected to be associated with inter-stratified mineral. FIG. 7.6.31 shows the relationship between the Hinckley Crystallinity Index and particle size (the 1 micron proportion being taken as indicative). The general trend which can be observed is that the coarser seams show the best crystallinity and the finer seams the greatest disorder in the kaolinite present. This trend is best shown by the Southacre Member, which shows the highest crystallinity value in the kaolinite silts, such as the Parks and the Chudleigh Knighton clays, and more disordered kaolinite in finer grained clays towards the south. The increased proportion of mica and occasional mixed layer mineral in the finest clays in the extreme south shows a further particle size control. Although it is possible that crystallinity could vary with grain size within a single provenance, the present author considers that a multiple provenance is indicated with the finest particles of disordered kaolinite being derived from the weathering products of
Fig. 7.6.31. Relationship Between Hinckley Crystallinity Index and Particle Size.

Fig. 7.6.32. Relationship Between Hinckley Crystallinity Index and pH.
country rocks, coarse well ordered kaolinite being derived from hydrothermal kaolins and medium ordered kaolinite being derived from a mixing of the two latter types or possibly by weathering of granitic felspar.

During Abbrook times, the Dartmoor granite was obviously making a considerable contribution to sedimentation, as is shown by the ubiquitous sub-hedral quartz and tourmaline. The disordered kaolinite, high mica and the general presence of interstratified mineral indicate, however, that most of the fine material was being derived from the country rocks. It is envisaged that, during Abbrook times, and to a certain extent during the earlier Lappathorn period, the Dartmoor granite, although obviously unroofed, generally contained numbers of roof pendants and xenoliths in the parts of the granite mass nearest to the Bovey Basin. These roof pendants and xenoliths together with fine material derived from the aureole and the coarser particles of granitic origin, make up the bulk of the sediments laid down at this time.

Later, during Southacre times, coarser hydrothermal kaolins, probably in association with the Sticklepath Fault, were being eroded, possibly from the site of the modern Lustleigh Valley, which reflects the Sticklepath Fault. These coarser well ordered kaolinites were deposited at the northern end, whilst the particles of finer aureole-derived disordered kaolinite were being carried further to the south, where they were deposited together with the finer particles of well ordered kaolinite, to give rise to a commercially important group of fine, medium ordered kaolinitic ball clays.

After Southacre times, only one seam of well ordered kaolinite has been recorded, this being in the Twinyeo Member. This indicates that, for some time, hydrothermal kaolin deposits were still being eroded and that the other medium ordered kaolinites of this member were a mixture of well ordered hydrothermal kaolin and poorly ordered
material derived from country rocks. Conversely, the only higher member which exhibits any seams of highly disordered kaolinite is the Stover Member in which there are two seams amongst the granitic sands. This indicates either derivation from another area of Dartmoor, which was just being unroofed, or that a dual provenance was in existence during sedimentation of these seams. The absence of any well ordered kaolinite suggests however that the hydrothermal kaolins had now been completely eroded - certainly there is no sign of them in modern times on the Bovey side of Dartmoor - so that the former premise is the more likely.

All the younger members are comparatively coarse and show medium ordered kaolinite. The emphasis of sedimentation had shifted to the north and west and indications are that derivation in these later members was from the west. Much of the western part of the basin has been faulted up and subsequently eroded away so that, at this time of sedimentation, the Bovey Basin probably extended westwards onto the Dartmoor granite itself. The absence of any extremes of crystallinity in the kaolinite suggests that there was one uniform source of kaolinite, namely weathered granitic felspar, which was finer than the hydrothermal kaolinite but coarser than the kaolinite derived from country rock (and also higher in iron than the Abbrook material, which is rather surprising).

The higher members contain kaolinite which is not as fine grained or as disordered as that of the Abbrook Member and, hence, do not have the plasticity of the commercially important Abbrook ball clays. Conversely, neither do they have the white firing characteristics of the well ordered kaolinites of the commercially important Southacre Member.

It is considered that the provenance is the major factor determining crystallinity. Transport and environmental factors can only decrease crystallinity. Transport is not considered to be a likely influence, as major chemical changes, such as those involved in
alteration to crystallinity, are unlikely to occur in the short distances involved during sedimentation of the Bovey Basin. However, leaching within the environment could affect the crystallinity. FIG. 7.6.32., however, shows that there is no relationship between pH and the crystallinity of kaolinite and merely shows that pH was mainly between 4 and 6. The highest pH recorded (6.9) was on a sideritic clay and the other two clays with a pH of more than 6 were both non-carbonaceous. The lowest value (3.2) was on a very carbonaceous clay. If the environment has affected the crystallinity, it is masked by the overriding control of the provenance.

7.7. Recognition of Dispersion.

The prepared sections of deflocculated and natural sediments showed some surprising differences.

The sections cut vertically through the sediment showed that, in the deflocculated sample, the particles were orientated and acted optically as one crystal. This showed illumination at about 45° to the cross-wires under crossed nicols (see PLATE 7.7.1.). On rotation of the stage to a position almost parallel to the cross-wires, extinction was produced at the kaolinite extinction angle of 1 to 3½° (PLATE 7.7.2. shows this condition just before complete extinction). Another feature which is evident on these plates is the desiccation cracks which only penetrate a comparatively small distance below the sediment surface. A feature which is not seen in the plates is the coarser material at the base of the sediment which grades upwards. Comparison with the natural sample indicates that desiccation cracks occur but that the apparent grading does not. Also, although some patchy extinction can be distinguished on a vertical section of undeflocculated sediment, no general extinction is discernible.
PLATE 7.7.1. Vertical Section Through a Settled Deflocculated Sample of an Abbrook Carbonaceous Clay - At the 45° Position. (Crossed Nicols x67)

PLATE 7.7.2. Vertical Section Through a Settled Deflocculated Sample of an Abbrook Carbonaceous Clay - At Extinction Position. (Crossed Nicols x67)
Horizontal sections through both samples reveal no apparent orientation but present very different appearances (PLATES 7.7.3 and 7.7.4). Both samples show desiccation cracks of typical hexagonal outline on the upper surface of the sediment. However, the texture of the sediments is entirely different. The deflocculated sample is uniform in appearance with some darker specks of carbon. All the coarse particles have settled to the lower surface. The undeflocculated sample shows a variegated patchy sediment with some fine quartz particles and dark blobs of carbon-rich floccs on the top surface indicating that settlement 'en masse' has occurred.

The result of this experiment is further evidence that the natural sediment was laid down in a flocculated condition since inspection of other thin sections rarely shows any signs of orientation and certainly none as spectacular as shown in the deflocculated sample. The texture of the natural sediment is also unlike that of the deflocculated sample.

7.8. The Sands.

Exposures of the sands are comparatively rare and are confined mainly to small sections within quarry sequences. Borehole samples are confined to material of no use for determining either structures or grain size analysis. Core samples are rare and are generally confined to what is euphemistically described as 'sand bound in clay' or to 'lumping sand'. Both of these sediments contain sufficient clay and silt grade material to prevent penetration of the drilling fluid and consequent washing out during the coring process. Interesting as these sediments are, they are not completely representative of the sands in the Bovey Basin.

As Southacre Pit is being developed to the west, sands in the lower part of the Stover Member are being exposed. T. M. Gouldstone,
PLATE 7.7.3. Desiccation Cracks in a Horizontal Section of Deflocculated Settled Abbrook Carbonaceous Clay (Plane Polarised x67)

PLATE 7.7.4. Desiccation Cracks in a Horizontal Section of Undeflocculated Settled Abbrook Carbonaceous Clay (Plane Polarised x67)
during research into the 'head' deposits, made a number of investigations of grain size. Two samples of sands, one from Southacre and one from Bovey Heath, were processed and computerised by Gouldstone on the author's behalf. FIG. 7.8.1. shows the computer analysis of a Lower Stover sand from Southacre Pit. This shows the sand to contain a tremendous range in grain size, with 16% gravel, 72% sand, 5% silt and 7% clay. Folks' textural description of the sediment is very poorly sorted gravelly, muddy sand. PLATE 7.8.1. is a photograph of this Stover sand seam and this shows a complete absence of any sedimentary structures (similar to the Lappathorn sand shown in PLATE 6.1., although the Lappathorn sand is much finer than this Stover sand). Underlying this Stover sand in Southacre Pit is a muddy sand with lighter coloured clayey, sandy silt laminations (see PLATE 7.8.2.). This seam rests directly on the Parks Seam which it oversteps to the south.

The Bovey Heath sand proved to be similar in grain size distribution but was an even less well sorted gravelly, muddy sand (gravel 26%, sand 46%, silt and clay 28%). A distinguishing feature of these Bovey Heath sands is the presence of felspar amongst the euhedral quartz grains and abundant tourmaline, a feature which is not seen in the Stover sands in Southacre Pit.

The range in grain size and the absence of sedimentary structures suggest settling 'en masse' from a turbid stream whose velocity is suddenly checked. These conditions are probably best explained by the outwash fan concept with streams rushing off the slopes of Dartmoor, turbid with granitic débris, being checked on reaching the comparatively low-lying, fairly flat Bovey Basin, and building fans which at times covered a considerable proportion of the whole basin. The laminated sands in Southacre Pit suggest that, at times, conditions were varying, apparently on a rhythmic basis.
THE PERCENTILES ARE

-1.990  PHI13
-1.650  PHI15
-1.400  PHI16
-1.070  PHI16
-0.830  PHI20
-0.600  PHI25
-0.370  PHI30
 0.410  PHI50
 1.300  PHI70
 1.530  PHI75
 1.920  PHI80
 2.350  PHI84
 4.700  PHI90
 8.500  PHI95
10.800  PHI97

GRAVEL PERCENT = 16.000  SAND PERCENT = 72.000  SILT PERCENT = 5.000  CLAY PERCENT = 7.000

CALCULATION OF FOLK STATISTICS

MDPHI = 0.410
MZ = 0.557
STANDARD DEVIATION SIGMA G = 1.700
INCLUSIVE STANDARD DEVIATION SIGMA I = 2.378
SKEWNESS SKG = 0.129
SKEWNESS SKI = 0.362
KURTOSIS KG = 1.953
KURTOSIS KNEIG = 0.664

CALCULATION OF MCCAMMON STATISTICS

SORTING = 2.553
MEAN = 0.926

FOLKS TEXTURAL DESCRIPTION

GRAVELLY MUDY SAND
VERY POORLY SORTED
VERY LEPTOKURTIC
FINE SKEWED

**FORTRAN ** STOP

Fig. 7.8.1. Grain Size Analysis of a Stover Member Sand from Southacre Pit.
Plate 7.8.1. Gravelly Muddy Sand at the Base of the Stover Member in Southacre Pit.

Plate 7.8.2. Sand with Silty Laminations at the Base of the Stover Member in Southacre Pit.
The spacings of the laminations are too irregular, however, to suggest a seasonal variation. Some of the laminations also pinch out, which suggests that the clayey silts were being deposited in small ponds and lakes in the outwash fans.

Although the evidence is limited because of the lack of exposure, all the available evidence points to the outwash fan as being the most likely mode of formation of the sands. As further exposures are developed, other structures may be found to suggest a deltaic or fluviatile environment but, at the present time, this is a matter for conjecture.

7.9. The Lignites.

Except for occasional vertical reed-like roots in some of the carbonaceous clays, no evidence has been found to suggest that any of the plant remains found in the clays and lignites grew in situ. The lignites must therefore have been transported in from the margins of the basin and the slopes of Dartmoor. Some smaller twigs and fragments of vegetation were dragged down in the 'en masse' settlement of the clays and sands. The bulk of the mass of floating vegetation would end up in the area furthest from the entry of the stream into the Bovey Basin. In this foul backswamp area, the waterlogged and rotting vegetation would be gathered and also many fine clay particles which form admixtures with the lignitic material, depending on drainage of the slurry element in the backswamp.

7.10. Summary of Results.

7.10.1. Moisture content depends more on lithology than on depth or time.

7.10.2. Bulk density varies with depth and lithology.
7.10.3. There are two particle size distribution curves, one deflocculated (ultimate) and one natural. Variations of particle size within a seam are small and, when they do occur, are of a coarsening upward type followed by sharp fining. This is considered to be caused by variations in flocculation and concentration.

7.10.4. Fine ball clays could not be settled in a deflocculated state. Fine grained carbon and fine quartz have a large influence on flocculation. Carbonaceous clays must have settled 'en masse' from high concentration slurries. Siliceous clays are completely flocculated and can settle from lower concentration slurries. pH influences the degree of flocculation but the original sedimentary conditions are unlikely to have been more acid than the present pH of a concentrated slurry of the ball clay.

7.10.5. TiO₂ is in the form of anatase and is authigenic on quartz. Fe₂O₃ is contained in the kaolinite lattice and the later Members have marginally higher iron contents.

7.10.6. Mineralogically, the ball clays show large quantities of kaolinite, with quartz, mica, felspar and anatase showing on most X-Ray Diffraction traces, and with siderite, tourmaline and interstratified mineral also being common. The Hinckley Crystallinity Index of the kaolinite varies from 0.15 to 0.79. The finest clays show the greatest disorder (Abbrook Member) and the coarsest kaolinite silts (Parks) the highest order. This is considered to be caused by variation in provenance, with the finest kaolinite particles being derived from country rock and, in particular, roof pendants and xenoliths, whilst the coarse kaolinite particles
were derived from hydrothermal kaolins on Dartmoor. In the case of the Southacre Member, the coarsest clays are in the north and the finest towards the south. The medium disordered kaolinite of medium particle size could be derived from a mixture of these two types (i.e. country rock or hydrothermal kaolin) or from weathering of felspar in the Dartmoor Granite.

7.10.7. Deflocculated clays in vertical section show orientation of the kaolinite crystals which act optically as one crystal. Typical hexagonal desiccation cracks were observed on the upper surfaces of the prepared samples.

7.10.8. The limited exposures of sand indicate that sedimentation occurred in the form of outwash fans, with occasional development of ponds and small lakes.

7.10.9. The lignites were transported into the Bovey Basin and gathered in a backswamp environment.
8. **MACROSCOPIC AND MICROSCOPIC STRUCTURES IN THE BALL CLAYS.**

8.1. **Grain Size and Shape.**

As with the sands, some of the ball clays show huge variations in grain size and generally show sub-hedral outlines to the quartz grains. These features are illustrated in PLATES 8.1.1., 8.1.2. and 8.1.3. (and PLATES 8.1.4., 8.1.5. and 8.1.6. in Appendix IV).

PLATE 8.1.1. shows a sandy, silty clay from the Heathfield Member. The large euhedral quartz crystal in the bottom right of the plate is approximately 0.7 mm long, which would put it in the coarse sand grade on the Wentworth Scale. Isolated grains of even larger dimensions are present and most show euhedral outlines with pitted edges. The birefringence colours shown in PLATE 8.1.1. are typical of the slices prepared from Carbowax impregnation of the Bovey material in that the slice is, of necessity, slightly thicker (about 40 microns) than normal thin sections of hard rocks and, consequently, higher order birefringence colours on the quartz crystals are general. The euhedral nature of the coarser particles indicates a Dartmoor origin for the quartz present and the tremendous range in grain size indicates that the sediment was settling 'en masse' from a flocculated turbid slurry.

PLATE 8.1.2. shows a more uniform silty clay with less variation in the size of the quartz grains which, being finer, show more irregular outlines. The largest particles in this clay are lumps of lignite which would normally be expected to float but which have also been dragged down during 'en masse' settling.

PLATE 8.1.3. shows a silt pod of irregular shape within a brown, slightly silty clay. The silt pod shows a large variation in grain size which is not evident in the brown finer material which surrounds it. The silt pod is also characterised by dark tourmaline.
Plate 8.1.1.
Sandy Silty Clay from the Heathfield Member.
(Crossed Nicols x 67).

Plate 8.1.2.
Silty Clay with Some Lignite Fragments - Stover Member.
(Crossed Nicols x 67).

Plate 8.1.3.
Silt Pod in Silty Clay.
Lower Abbroyk Member.
(Plane Polarised x 67).
which also has a large variation in grain size. Tourmaline is confined to fine specks in the main mass of the clay. These silt pods are considered to have been torn from a partially sedimented hydro-plastic material by the following turbid flood from which the resulting sediment settled 'en masse', the pods being randomly included. Such a structure is common in the ball clays.

The variation in grain size and sub-hedral nature of the quartz grains are also illustrated in PLATES 8.1.4., 8.1.5. and 8.1.6. in Appendix IV.

8.2. Petrology.

The presence of tourmaline in the coarser fractions is almost invariable. The most common occurrence is a blue variety with a strong body colour which often masks both the pleochroism and the birefringence, although slice thickness is of obvious importance. A less common reddish-brown variety shows similar characteristics, whilst a buff variety shows strong pleochroism and high birefringence colours. Two varieties of tourmaline are shown in PLATE 8.2.1., one a buff variety showing strong pleochroism, and the other a blue variety which shows weak pleochroism. PLATE 8.2.2., which shows the same section with crossed nicols, shows that the darker blue tourmaline is in the thickest part of the slice, as is shown by the polarisation colours of the adjacent quartz. Regardless of thickness, the body colour obviously masks the polarisation colours of this particular variety of tourmaline. The buff variety shows the typical high order polarisation colours of tourmaline when they are not masked by the body colour.

PLATE 8.2.3. shows a tourmaline-rich muddy sand in which blue and reddish-brown varieties of tourmaline are present. Tourmaline is also shown in PLATES 8.2.4., 8.2.5. and 8.2.6. (Appendix IV).
Plate 8.2.1.
Silty Clay Showing Pleochroic Tourmaline. Upper Aabrook Member
(Plane Polarised x 67).

Plate 8.2.2.
Same Slice as Plate 8.2.1, but with Crossed Nicols x 67.

Plate 8.2.3.
Tourmaline-rich Muddy Sand. Stover Member.
(Plane Polarised x 67).
Except for siderite and marcasite, quartz - usually showing sharp outlines of euhedral character - is the only other crystalline mineral which can be recognised under the microscope. The ubiquitous presence of mica and the presence of felspar, anatase and inter-stratified mineral, together with the kaolinite, are all much too fine to be recognised as individual grains under even the highest magnification available on the polarising microscope and their presence is recognised by X-Ray Diffraction techniques.

Reference to PLATES 8.2.1. to 8.2.6. shows that these minerals are common to all the various members and that it is only the proportions and the grain size that vary.

8.3.  **Lignite and Colloidal Carbon.**

Pieces of twig, wood, leaves and stems are very common in the ball clays. When this plant material reaches a high proportion, the sediment ranges through a lignitic clay (called 'figgy' in the clay industry - a name derived from the rough texture as the surface dries) to a clayey lignite. Carbon is also present in very fine form, usually giving a brown hue to the clay depending on the proportion of such fine particles. These fine carbon particles, which have a profound effect on unfired properties of the clay, do not cause any deterioration in fired colour, the darkest of brown clays often producing a very white product on firing.

PLATE 8.3.1. shows a piece of lignitised woody material from a carbonaceous seam in the Upper Abbrook Member. Such a piece of wood would undoubtedly have floated and could only have become part of the clay sediment by being entrained during 'en masse' settlement after being tumbled along in a turbid flood slurry roaring off the slopes of Dartmoor into the shallow lake and marsh environment of the Bovey Basin.
Plate 8.3.1.
Piece of Woody Material.
Upper Abbrock Member.
(Plane Polarised x 67).

Plate 8.3.2.
Piece of Infilled Wood.
Lignitic Facies, Southacre Member.
(Plane Polarised x 67).

Plate 8.3.3.
Infilled Stem.
Twinyeo Member.
(Plane Polarised x 67).
PLATE 8.3.2. shows an originally hollow piece of wood which has become infilled with a silty clay (this example is from the Lignitic Facies of the Southacre Member). The silty infill is different in character from the surrounding carbonaceous matter so the hollow was filled elsewhere before being transported. Eventually the increased weight would have aided the settlement of this piece of wood.

PLATE 8.3.3. shows a stem which has been infilled with a similar material to the matrix. Careful inspection of this slice (from the Twinyeo Member), particularly under crossed nicols, reveals an arcuate structure within the stem which suggests that the infill was squeezed in after or during sedimentation. Another infilled stem is illustrated in PLATE 8.3.4., and a very lignitic clay in PLATE 8.3.5., both plates being located in Appendix IV.

Three clays from the Southacre Member which contain fine grained carbon as well as lignitic material are shown in PLATES 8.3.6., 8.3.7. and 8.3.8. The first of these plates shows a carbonaceous slightly silty clay in which many of the fine carbon particles are grouped into large floccs within a lighter coloured matrix together with much lignitised vegetation. PLATE 8.3.7. shows a similar clay containing a little more fine quartz but which shows a more uniform dispersion of the carbon particles, although some carbon floccs are evident among the organic matter. PLATE 8.3.8. contains considerably more fine quartz and an orientation of fine lignite strands. Although this latter plate was taken with the nicols crossed, the carbon is as evenly distributed as is suggested by the photograph. It would appear from these three plates that the degree of carbon flocculation is proportional to the amount of fine quartz present which apparently induces a higher degree of flocculation than the carbon. The orientation of the lignite 'strands' in PLATE 8.3.8. is approximately parallel to the dip as the section is cut vertically through the specimen. Breaking the specimen horizontally
Plate 8.3.6.
Lignitic Clay.
Southacre Member.
(Plane Polarised x 67).

Plate 8.3.7.
Slightly Silty Lignitic Clay.
Southacre Member.
(Plane Polarised x 67).

Plate 8.3.8.
Silty Carbonaceous Clay.
Southacre Member.
(Crossed Nicols x 67).
shows the 'strands' are in fact mainly broken leaves, which must have been entrained in the silty carbonaceous clay slurry.

Most of the vegetation was obviously transported into the Bovey Basin although, occasionally, vertical reed-like roots can be seen in seams of carbonaceous ball clays indicating that, at times, the water cover became very shallow allowing the growth of some marsh and water plants.

8.4. Fossils.

The abundance of plant remains which are found in the Bovey Basin make up the sum total of fossil evidence, except for a doubtful beetle collected by Pengelley (1862). The absence of animal life is hardly surprising when the environments of deposition are considered. The turbid lakes with high concentrations of muddy sediment held in suspension and being rapidly re-charged with similar slurry as settlement was occurring, would not be conducive to the establishment of life. The stinking backswamp areas, full of rotting vegetation and giving off carbon dioxide, were also unlikely to be colonised by an organism which depended on oxygen for support.

Any animal which was unfortunate enough to wander into, fall into or be swept into the swamps, because of the normally acid conditions, would have been unlikely to have been preserved. Nevertheless, the complete absence of animal fossils is rather surprising.

The organisms shown in PLATES 8.4.1. and 8.4.2. could be the first animal fossils to be found in the Bovey sediments. The organism shown in PLATE 8.4.2. is a sheared organism similar to that shown in PLATE 8.4.1. and is found in the seam immediately below the unsheared specimen in the Carbonaceous Section of the Upper Abbrook Member.
Plate 8.4.1. Non-Vegetable Organic Remains ?. Upper Abbrook Member. (Plane Polarised x 67).

Plate 8.4.2. Sheared Organic Remains. Upper Abbrook Member. (Plane Polarised x 67).
The author, on first inspection, decided that the organism was a megaspore and sent a photograph to Dr. M. Boulter, of the North East London Polytechnic, for possible identification. Dr. Boulter replied that the organism, although it was the right size, was not a megaspore ("the four lined mark in the centre is certainly not a trilete mark which has three lines") and that he and his colleagues had not seen any similar plant material. The author did not consider it to be a crystal structure so concluded that it must be animal, possibly of the sponge type, although the 'spicules' do not conform to the normal configurations. A similar photograph was sent via Dr. Freshney to Dr. M. A. Calver of the Palaeontological Department of the Institute of Geological Sciences. Dr. Calver replied "The entire resources of the Palaeontological Department have been concentrated on the solution of the object in the photograph, but we have not been able to come to a definite decision. The general opinion is that it is not a microfossil as such. The suggestions which have been put forward are that it is a cross-section of a root filled with secondary material. The petrologists have suggested that it could be a grain of metamorphic mineral, but they would require the slide for checking".

The author considers that these puzzling objects are more spherical than cylindrical and therefore are not roots. Also, if it is mineral in origin, why does it only occur at one horizon? Obviously much further investigation will be required but, meanwhile, the origin and nature of these objects remain enigmatic.

8.5. Lamination.

Lamination and banded appearance are comparatively rare in the Bovey sediments and the only two examples seen both occurred in the upper part of the Twinyeo Member. PLATES 8.5.1. and 8.5.2. show an even lamination disturbed by a root. PLATE 8.5.1. was photographed
Plate 8.5.1. Laminations in Carbonaceous Silty Clay. Twinyeo Member. 
(Normal Light x 4).

Plate 8.5.2. Laminations in Carbonaceous Silty Clay. Twinyeo Member. 
(Crossed Nicols x 67).
during preparation of the thin section. The crack across the slice parallel to the laminations occurred during mounting of the slice. The rootlet must have grown down through the sediment after at least partial consolidation as the laminations are curved down slightly on each side of the rootlet. PLATE 8.5.2. is part of the thin section under crossed nicols (x 67). This photograph shows that the lamination is not due to any form of grading but to variation in the amount and form of carbon present. Each lamination does not therefore represent changes in the sedimentary environment but relates to changes in the provenance of the sediment.

One of the coarse kaolinitic clays of the Upper Twinyeo Member shows what appears to be micro-cross-lamination. PLATE 8.5.3. is a photograph taken during preparation of the thin section and shows fine lamination due to variation in carbon particles. These fine laminations are apparently truncated and overstepped by other laminations to give the appearance of a cross-lamination. PLATE 8.5.4. shows, at a much greater magnification, that the cross-lamination occurs also on a microscopic scale within apparently uniform sediment in this specimen. The sediment presents a uniform lighting when the microscope stage is rotated under crossed nicols, which indicates a complete lack of any orientation in the kaolinite laths. The cross-lamination lines must represent minute erosional surfaces where the sediment was in a stage beyond the hydroplastic state and becoming a quasi-solid. The next turbid flood would erode some of this solid material, which could then possibly contribute to a breccia which would be found elsewhere at a similar horizon. If the turbid current occurred whilst the material was in an early stage of consolidation (i.e. quasi-liquid to hydro-plastic stage) the surface of the sediment would be stirred and contorted. In the particular specimen, there is evidence of both types of structure. However, the absence of micro-cross-lamination generally in the Bovey Basin shows that
Plate 8.5.3. Micro-Cross Lamination. Twinyeo Member. (Normal Light x 4).

Plate 8.5.4. Micro-Cross Lamination. Twinyeo Member. (Crossed Nicols x 67).
the interval between successive turbid flood currents was not long enough to allow much consolidation of the previous sediment.


Occasionally brecciation has occurred with the ball clay seams. The most spectacular example of this structure is found in the carbonaceous seam of the Upper Abbrook Member. The area of brecciation is comparatively small, usually in a lenticular band an inch or so in thickness. PLATES 8.6.1., 8.6.2. and 8.6.3. show this brecciated seam at three different magnifications and along different planes. The individual constituent pieces show neither angular nor very rounded outlines, usually being fairly light in colour in a darker matrix, and showing considerable variation in size and shape and no apparent lineation. PLATE 8.6.3. shows that some of the lighter areas contain quartz particles in the silt grade, whilst the matrix contains little quartz silt. Inspection of some of the pieces reveals that they are brecciated within themselves. These brecciated areas must have been derived from pieces torn out of an underlying sediment in a quasi-solid state by the turbid current in which the dark matrix particles were being carried. The resulting 'en masse' settlement would contain slightly rounded pieces of all shapes and sizes composed of the partially consolidated sediment traversed by the current, which included an already brecciated sediment.

PLATES 8.6.4. and 8.6.5. show in plane polarised light and with crossed nicols another type of clay breccia. In this case, darker carbon-rich streamlined pieces of clay are surrounded by a lighter matrix, the latter showing some orientation and apparent flow structures. Other clays from the Clay Facies of the Southacre Member show a similar structure but both matrix and pieces in the breccia are of similar material. This type of material appears to have been formed when the
Plate 8.6.1.
Brecciated Clay. Carbonaceous Seam. Upper Abbrook Member. (Normal Light x 2).

Plate 8.6.5. Clay Breccia. Clay Facies of Southacre Member. (Crossed Nicols x 67).
turbid current has penetrated the upper layers of a quasi-liquid to hydro-plastic sediment and has flowed around the more resistant pieces of sediment and orientated the particles between. Unlike the breccia described from the Abbrook Member, the pieces of the breccia are not haphazard but are streamlined and aligned with the fine matrix showing a sort of flow structure. This fine grained material could not have been sedimented to give this pattern and must be the result of later re-alignment after initial sedimentation.

8.7. Microscopic Cracks and Fractures.

Two types of cracks on a microscopic scale appear in the ball clays. One type appears to radiate without any readily discernible pattern. PLATE 8.7.1. illustrates this type of cracking. The shape of these cracks is entirely different than that expected from desiccation (compare with PLATES 7.7.3. and 7.7.4.) which have hexagonal outlines. The cracks shown in PLATE 8.7.1., however, have no regular outline and the angles between are very variable and they are considered to be the result of a type of syneresis. As the highly concentrated flocculated slurry settled, the interference of the floccs would prevent the upward escape of water. The weight of the floccs would, however, increase the pressure below the mudline, leading to the development of cracks through which the water could escape upwards as the settling sediment went through quasi-liquid and hydro-plastic stages before becoming a quasi-solid. All the sediments in which these features have been seen are very fine grained. Another example is shown in PLATE 8.7.4. (Appendix IV).

The second type of cracking has occurred after the sediment has reached a solid state and is either due to the 'basining effect' of Saldivar Sali (1973) or to tectonic movement. The present author considers the latter premise to be more likely and that these almost
Plate 8.7.1.
Syneresis Cracks. Upper Abbrook Member.
(Crossed Nicols x 67).

Plate 8.7.2.
Tectonic Cracks. Clay Facies
Southacre Member.
(Crossed Nicols x 67).

Plate 8.7.3.
Micro-fault Breccia (?).
Twineyn Member.
(Crossed Nicols x 67).
rectilinear cracks are of tectonic origin. The specimens showing syneresis cracks probably also have tectonic cracks present as well. PLATE 8.7.2. shows a clay from the Southacre Member in which there are two well-defined tectonic fracture trends almost at right angles to each other. PLATE 8.7.5. (Appendix IV) shows a clay from the Twinyeo Member in which the included angle between the fractures is only some 70°. PLATE 8.7.6. (Appendix IV) shows a micro-fault infilled with Carbowax on which movement has been some three-quarters of a millimetre.

The fractures shown on PLATE 8.7.3. are more difficult to explain. At first sight, these cracks have an appearance which superficially suggests shrinkage. On closer inspection, however, few areas exhibit a typical hexagonal pattern and the variations in width of the cracks are large. The pattern is however too regular to be due to syneresis and the cracks occur in a narrow band across a thin section.

It is considered that this phenomenon is most likely to be a micro-fault breccia and that it took place after consolidation, as have the other tectonic features.

PLATES 8.7.7., 8.7.8. and 8.7.9. (Appendix IV) show uniform clays of varying silt content, with some poorly developed cracks of tectonic origin in evidence.

8.8. Siderite.

The iron-carbonate material, siderite, is fairly common in all the members but particularly so in the Great Plantation Member and in the Parks Seam at the top of the Southacre Member. PLATES 8.8.1. and 8.8.2. depict the Parks Seam, one at depth under Bovey Heath and the other in the Type Area.
Plate 8.8.1. Siderite in the Parks Seam at Depth Under Bovey Heath.
(Crossed Nicols x 67).

Plate 8.8.2. Siderite in the Parks Seam from the Type Area.
(Crossed Nicols x 67).
The Parks Seam under Bovey Heath is very much coarser than further south, hence the pore spaces would tend to be very much larger and the siderite growths larger. In the Type Area, PLATE 8.8.2. shows that the Parks is brecciated, with large areas of uniform grey material and intervening areas showing some degree of orientation, with fine siderite growths in both. The pH of this clay is 5.5, too low for the formation of siderite (the pH of other sideritic clays is normally near 7.0). It is considered that the pH of 5.5 was of the original sediment before pieces were removed and redeposited by the turbid current, the pH of which was sufficiently high to allow the formation of siderite.

As well as neutral pH, a source of carbonate is also required for the formation of siderite. This could come from two sources:

(i) Carbon dioxide formed with rotting vegetation

(ii) Limestone in the surrounding country rocks.

Parks contains sufficient vegetable matter to suggest that rotting vegetation was the source of the carbonate but the virtual absence of carbonaceous matter in the Great Plantation Member suggests that possibly the erosion of Devonian Limestones to the south-west of the Bovey Basin was providing a source of carbonate.

The other iron mineral, mundic (marcasite), is not evident on X-Ray Diffraction and is not easily seen on microscopic examination, although it is very common in the ball clays, particularly in the Abbrook and Southacre Members.

8.9. Summary.

8.9.1. There is a huge variation in grain size and quartz grains tend to be sub-hedral.
8.9.2. Quartz and tourmaline are almost ubiquitous except in the finest clays.
These first two conclusions indicate the granitic origin of the coarser particles and that settling 'en masse' must have occurred.

8.9.3. There are two types of carbon present:
(a) lignitised twigs, stems and leaves often with infilled hollows
(b) fine grained carbon, which is usually present in the largest floccs.
This vegetation was transported into the Bovey Basin.

8.9.4. A possible animal organism is found in the Carbonaceous Part of the Abbrook Member.

8.9.5. Laminations or banding are rare and, when they do occur, they are due to provenance changes rather than to grading.

8.9.6. Brecciation of two types occurs:
(a) by tearing out and redeposition of pieces of partially consolidated sediment
(b) by re-orientation of particles by penetration of a turbid current into a quasi-liquid to hydroplastic sediment.

8.9.7. Two types of micro-fracture can be recognised:
(a) due to syneresis
(b) due to tectonic activity.

8.9.8. Siderite growth depends on size of pore spaces, pH of the environment and a source of carbonate.
9. SEDIMENTARY ENVIRONMENTS AND PALAEOGEOGRAPHY.

9.1. The Sedimentary Environments.

From the evidence so far, there appear to be three basic environments:

(a) Outwash Fans
(b) Turbid Shallow Lakes
(c) Backswamps

The outwash fans environment gave rise to the large thicknesses of gravelly muddy sands which are very poorly sorted. The particles larger than clay grade appear to be wholly derived from the Dartmoor Granite.

The turbid shallow lakes gave rise to clayey silts and clays depending on the degree of flocculation and on the concentration of the slurry collecting in the lake and on the degree of circulation within the lake basin.

The backswamp environment gave rise to the lignites by the collection of the floating vegetation in the very shallow water furthest from the entry to the basin.

None of the environments described is conducive to any form of life except occasional reed-like water plants in the shallow lakes. The absence of any desiccation cracks suggests that the lakes did not dry out but were being constantly replenished with turbid water which, on the evidence of brecciation, must often have been moving fairly fast, perhaps down the slope created by an outwash fan.
The three types of environment sometimes occurred simultaneously in different areas of the Bovey Basin; at other times, two types or, more commonly, one type covered the whole of the sedimentary area.

The provenance also plays a very large part in the type of clay sediment laid down. Three types of provenance for the kaolinite can be recognised:

(i) Country rock (including roof pendants and xenoliths)
(ii) Hydrothermal kaolin deposits
(iii) Weathering of felspar in the granite

Added to these controls is the formation of siderite in the pore water when the pH of the environment rises to neutral and a source of carbonate is available. When the pH is lower, marcasite tends to grow especially around small seeds and twigs where radial growths are common.

The three types of environment shifted around the Bovey Basin due to changes in the focus of tectonic sagging. At the same time, the main provenance of Dartmoor was being lowered and fundamental changes in the amount and the nature were occurring in the material being supplied to the sedimentary environment. From this intricate sedimentological pattern, the complex Bovey Beds were laid down, probably throughout most of the Lower Tertiary.

9.2. The Abbrook Member.

The sedimentary area of the Lower and Middle Abbrook Member occupied an oval area stretching from the Bovey Heath area in the north to West and East Golds immediately to the north of Newton Abbot. (Fig. 9.2.1.). The largest axis of this roughly elliptical area trends in the north-west to south-east direction of the Sticklepath Fault System.
Outwash fans covered the whole area at times, giving rise to the very poorly sorted gravelly muddy sands in the Lower and Middle Abbrook Sequence. At other times, lakes of varying depths and varying concentration of suspended sediment occupied more limited areas, rarely expanding to fill the whole of the sedimentary area. The clays and clayey silts of the Lower and Middle Abbrook were sedimented in the lacustrine environment.

The general coarsening to the north-west indicates that the probable source was towards the present-day River Bovey Valley (i.e. along the Sticklepath Fault).

The coarser materials are exclusively of granitic origin, indicating that the Dartmoor Granite was exposed fairly close to the sedimentary area. The fine grained nature of the disordered kaolinite shows, however that the Dartmoor Granite was not unroofed nearly as much as it is at the present time. The fine disordered kaolinite was probably being derived from the roof, roof pendants and xenoliths in the parts of the granite near the roof. These conditions were unchanged throughout Abbrook Times.

The general absence of carbonaceous material or significant lignite bands below the Upper Abbrook is however puzzling. Is the reason for this anomaly climatic or sedimentary? It is possible that the lakes had an outlet at the south-eastern end and that the floating vegetation did not accumulate but was carried out of the sedimentary area. If this was so, many fine particles would also escape and the circulation within the lake would probably prevent settlement of some of the very fine grained clays which exist in the Lower and Middle Abbrook Member. On balance, the more likely explanation is one of climatic change, which allowed the establishment of a luxuriant
vegetation on the slopes of Dartmoor, the change occurring at the end of Middle Abbrook Times.

The sedimentary area in Upper Abbrook Times was similar in area and extent to that previously existing but it had become more complex (Fig. 9.2.2.), probably due to localised sagging within the main tectonic framework. Outwash fans generally existed over much of the north-western part of the sedimentary area, whilst most of the southern and south-eastern part of the basin was a backswamp environment. To the east, however, shallow lakes with a very high concentration of suspended sediment occupied the area which has become the most important for economic exploitation of ball clays. At times, these various environments expanded or shrank from these limits, hence seams of lignite are found in the clays of the lacustrine environment and seams of clay are found in the lignites of the backswamp environment. For the first time, both colloidal carbon and lignite are found in large quantities. The colloidal carbon adds another important constituent to the fine grained disordered kaolinite which places these seams of Upper Abbrook ball clay among the most important of ceramic raw materials.

As Upper Abbrook Times progressed, the sedimentary area began to shrink towards the north-west and the whole area was covered by outwash fans, giving rise to gravelly muddy sands with abundant pieces of lignite, and occasional lakes which probably had a fairly free circulation and outlet since only clayey silts are found with no fine grained carbonaceous clays or significant lignites. The clayey silts, however, are characterised by small lignite pieces which indicates that settlement must have been 'en masse', so either the finer kaolinite particles were not being supplied in sufficient quantity to lead to the formation of a clay or the concentration of the suspended sediment was not sufficient to entrain the fine particles during initial settlement, although less
dense, larger particles of lignite were entrained. If the lake had an outlet, then the fine particles still in suspension would have escaped together with the floating vegetation.

9.3. The Southacre Member.

The overlying Southacre Member rests with a small angular unconformity on the Abbrook Member. The sedimentary area in Lower Southacre Times (Fig. 9.3.1.) extended over a similar area to that of the Abbrook Member but extended further to the north and west and did not reach the East and West Golds areas until comparatively late in Lower Southacre Times. The north-west part of the sedimentary area was dominated by an outwash fan type of environment, whilst practically the whole of the southern and western part of the basin was dominated by backswamps. Shallow lakes however dominated an area in the north-east of the sedimentary area, stretching from the present Chudleigh Knighton Heath to Clay Lane and Newbridge. In the north of this latter area, sand bands interleave with the clays and, to the south, increasing lignite bands interstratified with the clays show how the outwash fans and backswamp environments encroached at times into the lake areas which were contracting, shifting and extending as the degree and focus of tectonic sagging changed.

The clays, as well as the sands, coarsen to the north-west of the Bovey Basin, indicating the direction from which the material was being derived. The kaolinite being fed into these environments shows well ordered characteristics and must have been derived from hydrothermal kaolins, probably associated with the Sticklepath Fault System, which were being eroded from the Lustleigh Valley (which is now occupied by the River Bovey).
Fig. 9.3.1. Lower Southacre Times.

Fig. 9.3.2. Upper Southacre Times.
Very little clay is found within the outwash fans or in the backswamp lignites, except during initial sedimentation when a shallow turbid lake existed for a short while covering practically the whole of the initial sedimentary area, which extended from Little Bradley in the north to Preston Manor in the east.

During Upper Southacre Times (Fig. 9.3.2.), the environment pattern became more complicated and the sedimentary area extended further to the south into what is now the faulted outlier of Decoy.

Outwash fans dominated, as before, the north-west of the sedimentary area but these extended further to the south over much of the western part of the then Bovey Basin. Shallow lakes still existed in the Chudleigh Knighton area and extended to the backswamps of the Twinyeo area. This backswamp environment, however, was very much smaller than before and most of the south-eastern part of the sedimentary area was covered generally by a lacustrine environment. Occasional lignites within the clays show how the backswamp environment re-established itself over the south-eastern part for limited periods of time.

Hydrothermal kaolins were obviously still being supplied to the Bovey Basin and the northern lake clays still show well ordered kaolinite. The southern lake was being supplied, however, from the west, as is shown by the coarsening of the clays in this direction. The kaolinite derived from this direction, although fine grained, probably contained not only particles derived from hydrothermal kaolins but also from other sources, so the resulting kaolinite shows greater disorder from the mixing of the two types. Nevertheless, the ball clay is still white firing which is one of the most important characteristics of these clays. Towards Decoy, the ball clays become even finer in particle size and contain slightly more disordered kaolinite, more fine mica and inter-stratified mineral and they become more like the carbonaceous clays of the Abbrook Member.
As Upper Southacre Times progressed, the southern lake shrank northwards, until Southacre Pit itself was reached, many of the upper clays in this pit not being found further to the south. During this period, the backswamp environment to the north continued to build up large thicknesses of lignite with only occasional lacustrine invasions.

The final sedimentary area of Southacre Times occupied a similar area to the initial Southacre sedimentary area, stretching from Bovey Heath to Southacre Pit, which must have been occupied by a lake. Into this lake was poured coarse well crystallised kaolinite, which formed beds of ball clay with similar properties to a refined china clay. Unfortunately, the pH of the lake rose and there was an abundant source of carbonate and the whole of the Parks Seam is full of siderite in the form of spherules or in powdery yellow bands which, on firing, produces large black spots and specks. Nevertheless, the Parks Seam is a distinctive marker band to close Southacre Times.

9.4. Twinyeo Member.

The sedimentary area for the first time became radically different from the earlier periods of time. The area contracted, reaching from Brimley to just south of the present confluence of the Rivers Teign and Bovey, the longest axis of the ellipse being now west-north-west to east-south-east rather than the previous north-west to south-east of the Southacre and Abbrook Members (Fig. 9.4.).

The north-western part of this sedimentary area is characterised by very poorly sorted gravelly muddy sands with very few clayey horizons. This sediment was derived from the nearby granite and laid down in outwash fans.
The south-eastern part was dominated by the backswamp environment and large thicknesses of lignite were accumulated with only occasional sandy, silty, carbonaceous clays, signifying any change in the environment. These clays are typically composed of medium ordered kaolinite and are fairly coarse grained and show little similarity to either of the two earlier members. Probably these kaolinites are medium ordered because they are either a mixture of well ordered kaolinite derived from erosion of hydrothermal kaolins and poorly ordered particles derived from the weathering of country rocks, or they are particles of kaolinite derived from the weathering of felspar in the granite. The coarse particle size distribution of these Twynyo clays when compared to the Upper Southacre clays, which do contain mixtures of the two types of kaolinite, suggests that the former premise is unlikely. However, the final clay beds of the
Twinyeo Member show that hydrothermal kaolins were still being eroded from Dartmoor. The final sedimentary area contracted considerably and probably only covered small areas around Heathfield and Drumbridge. This sedimentary area was filled with coarse well ordered kaolinite which, similar to the Parks Seam, is full of siderite and which in every other characteristic shows similarity to a china clay.

9.5. The Stover Member.

The sedimentary area now moved to the south-east, only the northern feathering edge of the Stover Member overlapping the southern part of the Twinyeo Member. The long axis of the roughly elliptical area returns to a basically north-west to south-east lineation. (Fig. 9.5.).
This sedimentary area stretched from just north of the present A38 road to East Golds in the south-east but shrank from these extremities after a comparatively short time, so that only the lowest very poorly sorted gravely muddy sands of granitic origin were deposited over the maximum sedimentary area. This initial sedimentary area of the Stover Member must have been covered by outwash fans. In fact, the whole of the Stover Member is dominated by outwash fans and the sands associated with them. Tectonic activity must have been very uniform over the sedimentary area at this time so that sufficient slope was maintained to prevent either the formation of lakes or backswamp environments to any great extent.

Sandy, silty clay seams show that occasionally lakes did develop in the outwash fans and finer particles were sedimented. The kaolinite in these clay seams is generally fine grained and very poorly ordered, suggesting an origin similar to that of the Abbrook Member and derived from country rock rather than the Dartmoor Granite. One seam in the middle of the Stover Member, however, shows many of the characteristics of Parks, with the usual coarseness, lack of mica and white firing, but containing much less siderite and not as well ordered kaolinite, but which must still have been derived from hydrothermal kaolins on Dartmoor.

Some evidence has also been found recently to suggest that the possible clay facies of the Stover Member contains coarse well ordered kaolinite. Nevertheless, the seam in the middle of the Stover Member is the last known occurrence of a comparatively well ordered kaolinite in the sedimentology of the Bovey Basin, and it must be assumed that, at this time, the last china clay deposits were being removed from the south-eastern part of Dartmoor and the last of the white firing ball clays was being laid down in the Bovey Basin.
The true position of the Blatchford Member is a matter for conjecture. Certainly, it rests on part of the Stover Member so sedimentation must be later than Stover Times. However, the Blatchford Member is not overlain by any other member so could have been laid down at any time after the sedimentation of the Stover Member. To the south of Newton Abbot, the upper part of the Decoy outlier is filled with similar material which, in the absence of any other evidence, is conjectured to be part of the same Member.

The sedimentary area for this enigmatic member extended in a north-west to south-east direction from Twelve Oaks in the north to Aller in the south, in an apparently elongated but constricted tongue, which was widest in the area to the north of Newton Abbot. (Fig. 9.6.)
The whole of this area was occupied by outwash fans for a long period and is filled with gravely silty sands of granitic origin and contains very few particles in the clay grade.

Whether the sands of the Blatchford area and those of the Deccy area are contemporaneous or whether the Blatchford Member was laid down next after the Stover Member remains conjectural but certainly both areas were dominated by similar outwash fan environments during deposition of the sands.

9.7. The Brimley Member.

Until Brimley Times, the unconformities which exist between the various members have not been large. Although it is true that the Twinyeo Member and Stover Member occupied almost completely different areas of sedimentation, neither rests with much angular discordance on the Southacre Member. The Blatchford Member also shows little angular discordance on the Southacre Member which is a very good reason for placing the Blatchford Member in the earlier group of members rather than in the later group of members when the sedimentation area moved to the west and north. These later members rest with a marked angular discordance on the western outcrop of the earlier group. The Brimley Member is the earliest of the later group of members which has buried the western outcrop of the earlier members under a considerable volume of sediment and is the reason for the lack of ball clay working on the western side of the Bovey Basin - a fact which was first noted by Key (1862).

The Brimley Member originally spread much further to the west than the present-day western boundary of the Bovey Basin, which is formed by a considerable fault. The sedimentary area, which is shown as an ellipse on Fig. 9.7., has the longest axis running almost east-west and
was probably being filled from the west. The whole of the western part of the sedimentary area, which has subsequently been removed after uplift along the western boundary fault, was probably occupied by outwash fans, a premise which is supported by the poorly sorted sands on this horizon immediately to the east of Liverton.

The main part of the sedimentary area still extant within the Bovey Basin was dominated for the first half of Brimley Times by the backswamp type of environment with bands of carbonaceous, often silty clays signifying the development of occasional lakes. During the last half of Brimley Times, the whole sedimentary area was covered by outwash fans with the development of occasional lakes.

The sands are of obvious granitic origin but the clays contain kaolinite showing medium disorder and are medium grained. The derivation
of the kaolinite is conjectural. The sedimentary area at the time of deposition must have extended westwards practically onto the granite margin and most of the collected débris must have been of granitic origin. The kaolinite is therefore most likely to have been derived from weathering of granitic felspar.

The large thicknesses of Brimley lignites are the last occurrence of significant thicknesses of lignite in the Bovey Basin. This might well be due to further climatic changes but it is considered more likely to be due to the non-occurrence of backswamp environments to any great extent during the sedimentation of the later members.

9.8. The Heathfield Member.
This comparatively clay-rich member occupied one of the smallest of sedimentary areas of any of the members in the Bovey Basin, diameter being a roughly circular area only about one kilometre in the centre of the present basin. (Fig. 9.8.).

In early Heathfield Times, outwash fans and poorly sorted granitic sands dominated the sedimentation. The later Heathfield period however saw the formation of clays in dominantly lacustrine environments. These clays are not very fine grained and contain kaolinite of medium disorder, as well as sub-hedral quartz and tourmaline in the coarser fraction. These facts suggest a derivation almost wholly from the granite, the kaolinite being derived from the weathering of granitic felspar. Many of the clays are brown in colour, indicating that colloidal carbon was still being supplied to the original flood slurries but lignite is rare in this member which saw the laying down of the final seams of commercial ball clay in the Bovey Basin (the Heathfield Member having been worked for ball clay in the Heathfield Pit of Candy & Company).

9.9. The Great Plantation Member.

The sedimentary area during Great Plantation Times assumed a rough elliptical area, with an axis running north-east to south-west at right angles to the Sticklepath Fault direction. Much of this sedimentary area was outside the confines of the present Bovey Basin and has been removed by erosion after uplift. (Fig. 9.9.).

The whole of the sedimentation was dominated by outwash fans with very poorly sorted gravelly muddy sands of granitic origin. Lakes obviously developed over limited areas and periods within the sedimentary area and clayey silts and very silty clays resulted. The kaolinite contained in the 'clayey' areas shows medium disorder and not very fine
particle size and is considered to be derived from the weathering of granitic felspar, and to be carried into the sedimentary area from the west.

The sands, silts and clays of the Great Plantation Member are characterised by abundant siderite. Brown clays and lignites are rare in the member and, consequently, the pH of the environment was generally near 7.0. However, the absence of the organic acids required to lower the pH and the absence generally of carbonaceous material precludes the presence of rotting vegetation which could provide the CO₂ as a source of carbonate in the formation of siderite. It appears likely that the source of carbonate was the Devonian Limestones to the south-west of the Bovey Basin with a supply of carbonate-rich water into an environment with an already near-neutral pH and which, because of its coarse character, provided large pore spaces within the unconsolidated
sediment, which proved ideal for the formation of siderite. Whether the sedimentary area extended as far to the south-west as is shown in Fig. 9.9. is a matter for pure conjecture as there is certainly no evidence to substantiate the possibility. However, the present-day strike of the Great Plantation strata at right angles to the western boundary fault indicates that the sedimentary area was certainly beyond the present confines of the Bovey Basin.

9.10. The Bovey Heath Member.

The final phase of sedimentation in the Bovey Basin shows a more irregular shape than that of any of the earlier members. (Fig. 9.10.).

Fig. 9.10. The Bovey Heath Member.
The sedimentary area was confined to an area covering the north-western part of the basin and appears to have been mainly within the boundaries of the present-day Bovey Basin. The whole of the Bovey Heath Member is dominated by very poorly sorted gravelly muddy sands of, again, obviously granitic origin. Some of the material in surface pits shows some evidence of reworking. The sole seam of clay, found towards the base of the member, is extremely variable in both particle size and mineralogy, which suggests derivation from a previously deposited Bovey sediment. Much of the material was probably derived from the erosion of the Brimley and Great Plantation Members uplifted along the western boundary fault but the presence of quite large sub-hedral felspar crystals at the northern end of Bovey Heath shows that the adjacent parts of the granite were also supplying material to the Bovey Heath Member, probably from the north-west.

9.11. **Summary.**

The sedimentological history of the Bovey Basin is very complex. Three types of environment occurred, namely outwash fans, lakes and backswamps, which were controlled by localised tectonic sagging, with movement of the focus of sedimentation around the basin. Three types of provenance occurred, namely hydrothermal kaolin, weathering of country rock and weathering of granite, and the prevalence of one type or the mixing of the types was responsible for variation in both the particle size and crystallinity of the kaolinite being supplied to the sedimentary environment. All the coarser particles are of granitic origin.

The Abbrook Member was being sedimented whilst the adjacent granite still contained much roof material and a climatic change occurred during the later part of the period which allowed carbonaceous material to accumulate in lake and backswamp environments.
The Southacre Member saw the development of all three types of environment contemporaneously and the derivation of kaolinite mainly from hydrothermal kaolins in association with the Sticklepath Fault.

The later Twinyeo Member shows outwash fan sands and backswamp lignites, the Stover and Blatchford Members are dominantly outwash fan sands, any kaolinite being of probable mixed provenance.

This earlier group of members is probably of Eocene Age.

The focus of sedimentation then moved to the north and west and much of this later sediment has been removed during later uplift along the western boundary fault. The kaolinite in the upper members appears to have been derived from the weathering of granitic felspar. The Brimley Member contains the final accumulation of significant lignites, of probable Oligocene Age. After this time, a further climatic change may have occurred. The Great Plantation Member contains considerable siderite, the necessary carbonate being derived from the adjacent Devonian Limestone.

The final Bovey Heath Member contains much reworked material and is possibly representative of one of the later Tertiary Periods.
10. SUMMARY AND CONCLUSIONS.


The Bovey Basin is the most important of three areas of 'ball clay' in the South-West of England, the name 'ball clay' being derived from the original method of working. The mineral is basically a fine grained kaolinite with a variable quartz and carbon content, the beds of ball clay being interstratified with sands and lignite.

The Bovey Basin was tectonically controlled in association with the Sticklepath Fault System and the rock base is over 900 metres (3000 feet) in depth at the deepest point (possibly reaching 1300 metres - 4200 feet).

10.2. Techniques.

Particle Size Distribution curves are most important in evaluation of ball clays. These measurements were laborious and tedious until the advent of the Sedigraph 5000 Particle Size Analyser.

The behaviour of fine particles in a slurry has received very little attention in sedimentology although, in ceramic use, their behaviour has been extensively studied. The sedimentological aspects were investigated using the settling technique under conditions of varying pH, concentration and deflocculation.

The chemical characteristics of the ball clays were investigated by X-Ray Fluorescence and the mineralogy by X-Ray Diffraction.

Thin sections of the ball clay cores were prepared after impregnation with Carbonwax 6000.
Variations in natural moisture content (on the wet weight basis) were investigated.

10.3. Stratigraphy and Structure.

The Bovey Basin has had a complex sedimentological history and was probably being filled throughout the Lower Tertiary.

Ten members can be recognised, with unconformities (often with little angular discordance) between each member.

These members are as follows:-

Bovey Heath Member
Great Plantation Member
Heathfield Member
Brimley Member

Large unconformity between the earlier and later group of members.
The focus of sedimentation moved to the west and north after Blatchford (?) and Stover Times.

Blatchford Member
Stover Member
Twinyeo Member
Southacre Member
Abbrook Member
Lappathorn Member

The Southacre, Twinyeo and Brimley Members include large thicknesses of lignite.
The two commercially important members, and therefore the best known, are the Abbrook and Southacre Members. These two members have been exploited around the eastern outcrop for 250 years, but the western outcrop is buried under the later group of members.

Faulting is common. The western boundary of the Bovey Basin is a large fault parallel to the Sticklepath Trend, as are the minor faults in the northern half of the basin. The south-western margin is thrust and faulting within the basin in the extreme south has a north-east/south-west trend, which gradually swings to a north-south trend in the Preston Manor area. This fault pattern is considered to have been caused by Alpine movements from the south being deflected to the east by the stable block of Dartmoor.

10.4. Results.

10.4.1. Moisture content and bulk density vary with lithology and, to a lesser extent, with depth.

10.4.2. There are two particle size distribution curves, one deflocculated (Ultimate) and one natural. Variations in particle size within a seam are small and, when they do occur, are of a coarsening upward type followed by sharp fining. This is considered to be caused by variation in flocculation and concentration.

10.4.3. Fine ball clays could not have settled in a deflocculated state. Fine grained carbon and fine quartz have a large influence on flocculation. Carbonaceous clays must have been settled "en masse" from high concentration slurries. Fine grained siliceous clays are completely flocculated and can settle from low concentration slurries.
pH influences the degree of flocculation, but the original sedimentary conditions are unlikely to have been more acid than the present pH of a concentrated slurry of ball clay.

10.4.4. TiO₂ is in the form of anatase and is authigenic on quartz. Fe₂O₃ is contained in the kaolinite lattice and the later members have marginally higher iron contents.

10.4.5. Mineralogically, the ball clays show large quantities of kaolinite, with quartz, mica, felspar and anatase showing on most X-Ray Diffraction traces and with siderite, tourmaline and interstratified mineral also being common. The Hinckley Crystallinity Index of the kaolinite varies from 0.15 to 0.79. The finest clays show the greatest disorder (Abbrook Member) and the coarsest kaolinite silts (Parks) the highest order. This is considered to be caused by variation in provenance with the finest kaolinite particles being derived from country rock and, in particular, roof pendants and xenoliths, whilst the coarse kaolinite particles were derived from hydrothermal kaolins on Dartmoor. In the case of the Southacre Member, the coarsest clays are in the north and the finest towards the south. The medium disordered kaolinite of medium particle size could be derived from a mixture of these two types (i.e., hydrothermal kaolin and country rock) or from weathering of felspar in the Dartmoor Granite.

10.4.6. Deflocculated clays in vertical sections show orientation of the kaolinite crystals which act optically as one crystal. Such a feature is not seen in the prepared thin sections, although occasional 'patchy' orientations occur. This is further evidence that the ball clays were sedimented in a flocculated state.
10.4.7. The ball clays often show a high variation in grain size with particles ranging in size from coarse sand to fine clay. Quartz and tourmaline are almost ubiquitous except in the finest clays. These two conclusions indicate the granitic origin of the coarser particles and that settling 'en masse' must have occurred.

10.4.8. There are two types of carbon present in the ball clays.
   (a) Lignitised twigs, stems and leaves often with infilled hollows.
   (b) Fine grained carbon, which is usually present in the largest flocs.

   This vegetation was transported into the Bovey Basin.

10.4.9. Animal fossils are absent from the Bovey Basin except for an enigmatic object found in the carbonaceous part of the Abbrook Member.

10.4.10. Laminations or banding are rare and, when they do occur, they are due to provenance changes rather than to grading.

10.4.11. Brecciation of two types occurs:
   (a) By tearing out and redeposition of pieces of partially consolidated sediment.
   (b) By re-orientation of particles by penetration of a turbid current into a quasi-liquid to hydro-plastic sediment.

10.4.12. Desiccation cracks of recent origin and in prepared specimens show typical hexagonal patterns which are absent from any of the clays inspected. This suggests that the sedimentary environment of the clays did not dry out, although occasional reed-like roots suggest that the water became very shallow.
10.4.13. Two types of micro-fracture can be recognised:
(a) due to syneresis.
(b) due to tectonic activity.

10.4.13. Marcasite and siderite are common. Marcasite grew under fairly acid conditions, but siderite growth depended on the size of the pore spaces, a neutral pH and a source of carbonate.

10.4.15. The sands show a very poorly sorted character and a general absence of any sedimentary structures. The sands are virtually completely derived from the Dartmoor Granite.

10.4.16. The absence of roots and seat earths and the broken nature of the vegetation indicate that the lignites were transported into the Bovey Basin.

10.5. The Sedimentary Environments.

10.5.1. The clays were sedimented from flocculated turbid slurries feeding into a lacustrine environment. The absence of desiccation cracks suggests that the lakes rarely dried out completely, although the occasional reed-like roots suggest that the lake became shallow. The change in the type of environment was either by deepening of the lake and deposition of clayey silts, or by the collection of plant debris as the lake became very shallow, giving rise to lignites. These turbid lakes were being constantly replenished by flood slurries rushing off the slopes of Dartmoor which, on occasions, acted as turbidity currents within the lake giving rise to brecciation.
10.5.2. The lignites are mainly plant remains of all shapes and sizes with various admixtures of clay. The plant remains were swept into the Bovey Basin, probably with the flood slurries from which many of the clays were sedimented. The floating vegetation would have collected in the shallows furthest from the entrance to the lake forming a stinking backswamp environment.

10.5.3. The sands, being very poorly sorted and exhibiting no sedimentary structures, are considered to have been laid down in outwash fans.

10.5.4. The three types of environment shifted around the Bovey Basin with changes in the focus of tectonic sagging. The three types sometimes occurred simultaneously within the basin or, occasionally, one environment covered the whole of the sedimentary area. More rarely, two types of environment co-existed and, at one time (Upper Southacre), similar environments occupied two different sites within the sedimentary area.

10.5.5. *Provenance.*

The coarser crystalline particles were almost exclusively derived from the Dartmoor Granite.

The kaolinite had three possible provenances:

(a) fine grained disordered kaolinite derived from country rocks including roof pendants and xenoliths.

(b) coarse grained well ordered kaolinite derived from hydrothermal kaolin deposits.

(c) Medium grained medium disordered kaolinite which, in some cases, is a mixture from the other two provenances or was derived from the weathering of felspar in the granite.
The complex patterns of the changing sedimentary environments controlled by tectonic sagging and the changing provenance of the kaolinite has given rise to the intricate stratigraphy of the Bovey Basin.

The Abbrook Member was being sedimented in a dominantly outwash fan and lacustrine environment whilst the adjacent granite still contained much roof material. A climatic change occurred during the later part of the period which allowed carbonaceous material to accumulate in lake and backswamp environments.

The Southacre Member saw the development of all three types of environment contemporaneously and the derivation of kaolinite mainly from hydrothermal kaolins in association with the Sticklepath Fault.

The later Twinyeo Member shows outwash fan sands and backswamp lignites, the Stover and Blatchford Members are dominantly outwash fan sands, any kaolinite being of probably mixed provenance. This earlier group of members is probably of Eocene age.

The focus of sedimentation then moved to the north and west burying the western outcrop of the earlier members. Much of this later sediment has been removed during later uplift along the western boundary fault. The kaolinite in the upper members appears to have been derived from the weathering of granitic felspar. The Brimley Member contains the final accumulation of significant lignites, of probable Oligocene age. After this time, a further climatic change may have occurred. The Great Plantation Member contains considerable siderite, the necessary carbonate possibly being derived from the adjacent Devonian Limestones.
The final Bovey Heath Member contains much reworked material and is possibly representative of one of the later Tertiary Periods.

10.7. Variation of Geotechnical Properties (See Appendix 5)

Moisture content, Liquid Limit, Plastic Limit and Plasticity Index increase with:

(a) Increase in fineness of particle size distribution.
(b) Increasing disorder of the kaolinite (within individual Stratigraphic Members).
(c) Decreasing Silica Content.
(d) Increasing Carbon Content.

Other factors influence the Geotechnical Properties, such as the form of the carbon present, and the amounts of felspar, mica and interstratified mineral present. These factors have a considerable influence, but cannot be quantified.

The variation in Liquidity Index is considered to show that secondary consolidation on a geological time scale has produced varying degrees of overconsolidation depending upon the lithology of the ball clay.

The general conclusion reached is that the Geotechnical Properties of the ball clays depend largely upon the lithology of the sediment.
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APPENDIX I

Figs. 7.3.9. to 7.3.35.
Fig. 7.3.9. Particle Size Analysis of a Sideritic Clay from the Great Plantation Member.

Fig. 7.3.10. Particle Size Analysis of a typical clay from the Heathfield Member.
Fig. 7.3.11. Particle Size Analysis of a typical clay from the Brimley Member.

Fig. 7.3.12. Particle Size Analysis of a silty clay from the Stover Member.
Fig. 7.3.13. Particle Size Analysis of a Low Silica Clay from the Stover Member.

Fig. 7.3.14. Particle Size Analysis of a typical clay from the Stover Member.
Fig. 7.3.15. Particle Size Analysis of a Brown Silty Clay from the Twinyeo Member.

Fig. 7.3.16. Particle Size Analysis of a Low Silica Sideritic Clay from the Twinyeo Member.
Fig. 7.3.17. Particle Size Analysis of a Carbonaceous Clay from the Twinyeo Member.

Fig. 7.3.18. Particle Size Analysis of a very silty clay from the Twinyeo Member.
Fig. 7.3.19. Particle Size Analysis of a Medium-Ordered Kaolinite from the Clay Facies of the Southacre Member.

Fig. 7.3.20. Particle Size Analysis of a Well-Ordered Kaolinite from the Clay Facies of the Southacre Member.
Fig. 7.3.21. Particle Size Analysis of the Parks Seam from the Southacre Member at depth under Bovey Heath.

Fig. 7.3.22. Particle Size Analysis of the Parks Seam from the Type Area.
Fig. 7.3.23. Particle Size Analysis of a Silty Clay from the Upper part of the Lignitic Facies of the Southacre Member.

Fig. 7.3.24. Particle Size Analysis of a Slightly Silty Clay from the Upper part of the Lignitic Facies of the Southacre Member.
**Fig. 7.3.25.** Particle Size Analysis of a Carbonaceous Clay from the Lignitic Facies of the Southacre Member.

- **Percent less than e.s.d.**
  - Natural Ultimate:
    - 20μ: 74% 94.5%
    - 10μ: 63% 86%
    - 5μ: 50% 73.5%
    - 2μ: 31% 51%
    - 1μ: 19% 36%

- **pH of 1% sodium natural clay:** 5.45

---

**Fig. 7.3.26.** Particle Size Analysis of one of the few Low Silica Clays from the Sandy Facies of the Southacre Member.

- **Percent less than e.s.d.**
  - Natural Ultimate:
    - 20μ: 74% 94.5%
    - 10μ: 63% 86%
    - 5μ: 50% 73.5%
    - 2μ: 31% 51%
    - 1μ: 19% 36%

- **pH of 1% sodium natural clay:** 5.2
Fig. 7.3.27. Particle Size Analysis of a Low Carbon Clay from the Chudleigh Knighton area of the Southacre Member Clay Facies.

Fig. 7.3.28. Particle Size Analysis of a Slightly Silty Semi-Carbonaceous from the Abbrow Member.
Fig. 7.3.29. Particle Size Analysis of a Carbonaceous Clay from the Abbrook Member.

Fig. 7.3.30. Particle Size Analysis of a Slightly Silty Clay from the Abbrook Member.
Fig. 7.3.31. Particle Size Analysis of a Silty Clay from the Abbrook Member.

Fig. 7.3.32. Particle Size Analysis of an Extremely Silty Clay from the Abbrook Member.
Fig. 7.3.33. Particle Size Analysis of a Clayey Silt from the Abbrook Member.

Fig. 7.3.34. Particle Size Analysis of a Slightly Clayey Silt from the Abbrook Member.
Fig. 7.3.35. Particle Size Analysis of an Extremely Silty Clay from the Lappathorn Member.
APPENDIX II
APPENDIX 2

Calculation of Slurry Concentration

\[
\% \text{ solids} = \frac{S}{S - 1} (\rho - 1) \times 100
\]

where \( S \) is the specific gravity of the solid and \( \rho \) is the density of the slurry. \( \frac{S}{S - 1} \) is a constant, which can be computed from the specific gravity of the clay, which is generally taken as being 2.62. The constant therefore is 1.617.

Hence

\[
\% \text{ solids} = 161.7 (\rho - 1)
\]

and

\[
\rho = \frac{\% \text{ solids}}{161.7} + 1
\]

The starting slurry density, at 8% solids computes to 1.049. The slurry density under the mudline (\( \rho_m \)) can be computed from the weight of starting solid (\( W_s \)), the volume under the mudline (\( V_m \)), and weight and volume of water (\( W_w \) and \( V_w \)) and the density of the solid \( \rho_s \), all weights being in grams and volumes in cc's.

\[
\rho_m = \frac{W_s + W_w}{V_m}
\]

\[
\rho_m = \frac{W_s + (V_w \times 1)}{V_m}
\]

\[
\rho_m = \frac{W_s + V_m \cdot V_s}{V_m}
\]

\[
\rho_m = \frac{W_s - W_s + V_m}{V_m}
\]

\[
\rho_m = \frac{W_s \cdot (1 - \frac{1}{\rho_s}) + 1}{V_m}
\]

\[
\rho_m = \frac{0.617 \cdot W_s + 1}{V_m}
\]

The starting density in each case was adjusted to 8% solids.
\[
1.049 = \frac{0.618 \, W_s}{1000} + 1
\]

or

\[
0.618 \, W_s = 49
\]

\[
\rho_{\text{m}} = \frac{49}{V_{\text{m}}} + 1
\]

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<th>Slurry Density</th>
<th>% solids W/W</th>
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<tr>
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<td>1.061</td>
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</tr>
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<td>700</td>
<td>1.070</td>
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</tr>
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<td>600</td>
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<td>13.1</td>
</tr>
<tr>
<td>500</td>
<td>1.098</td>
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<tr>
<td>100</td>
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<td>79.2</td>
</tr>
</tbody>
</table>

Starting Concentration 1.049 (8% solids)
APPENDIX III

Figs. 7.6.2. to 7.6.30.
FIG. 7.6.3. X-Ray Diffraction Trace of a Sandrock from the Great Plantation Member.
FIG. 7.6.4. X-Ray Diffraction Trace of a Sideritic Clay from the Great Plantation Member.
FIG. 7.6.6. X-Ray Diffraction Trace of a Typical Clay from the Brimley Member.
FIG. 7.6.8. X-Ray Diffraction Trace of a Low Silica Clay from the Stover Member.
FIG. 7.6.11. X-Ray Diffraction Trace of a Low Silica Sideritic Clay from the Twinyeo Member.
FIG. 7.6.15. X-Ray Diffraction Trace of a Typical Well-Ordered Kaolinite from the Clay Facies of the Southacre Member.
FIG. 7.6.19. X-Ray Diffraction Trace of a Slightly Silty Clay from the Upper Part of the Lignitic Facies of the Southacre Member.
FIG. 7.6.20. X-Ray Diffraction Trace of a Carbonaceous Clay from the Lignite Facies of the Southcress Member.
FIG. 7.6.21. X-Ray Diffraction Trace of One of the Few Low Silica Clays from the Sandy Facies of the Southacre Member.
FIG. 7.6.22. X-Ray Diffraction Trace of a Low Carbon Clay from the Chudleigh Knighton Area of the Southacre Member Clay Facies.
FIG. 7.5.24. X-Ray Diffraction Trace of a Carbonaceous Clay from the Abbrev Member.
FIG. 7.6.20. X-Ray Diffraction Trace of a Slightly Clayey Slit from the Abbeek Member.
FIG. 7.6.30. X-Ray Diffraction Trace of a Clayey Silt from the Lappathorn Member.
APPENDIX IV
Plate 8.1.4.
Sandy Silty Clay with Some Lignite. Twirney Member.
(Plane Polarised x 67).

Plate 8.1.5.
Sandy Silty Tourmalinitic Clay. Bovey Heath Member.
(Crossed Nicols x 67).

Plate 8.1.6.
Silty Clay. Upper Abbrook Member.
(Crossed Nicols x 67).
Plate 8.2.4.
Pleochroic Tourmaline in the Bovey Heath Member.
(Plane Polarised x 67).

Plate 8.2.5.
Tourmaline-rich Sandy Clayey Silt.
Upper Abbrook Member.
(Plane Polarised x 67).

Plate 8.2.6.
Tourmaline in Silty Clay.
Middle Abbrook Member.
(Crossed Nicols x 67).
Plate 8.3.4.
Infilled Stem. Twineyo Member.
(Crossed Nicols x 67).

Plate 8.3.5.
Lignite Clay. Twineyo Member.
(Crossed Nicols x 67).
Plate 8.7.4.
Syneresis Cracks. Middle Abbroad Member.
(Crossed Nicols x 67).

Plate 8.7.5.
Tectonic Fractures. Twinyeo Member.
(Crossed Nicols x 67).

Plate 8.7.6.
Small Fault. Base of Southacre Member.
(Plane Polarised x 67).
Plate 8.7.7.
Uniform Slightly Silty Clay.
Clay Facies, Southacre Member.
(Crossed Nicols x 67).

Plate 8.7.8.
Uniform Silty Clay.
Upper Abbrook Member.
(Crossed Nicols x 67).

Plate 8.7.9.
Uniform Clay Showing Some Slight Patchy Orientation.
Middle Abbrook Member.
(Crossed Nicols x 67).
APPENDIX V

Geotechnical Properties of the Ball Clays.
Appendix 5: GEOTECHNICAL PROPERTIES OF THE BALL CLAYS.

A.5.1. Introduction.

The main interest in the properties of the ball clays have been confined to the ceramic properties of the sediment as a source of raw material. The author's main interest in the ball clay has been as a source of this raw material, whereas the geotechnical properties are concerned with the behaviour of a soil when under load. As a prospecting geologist, the last thing that the author would consider would be putting a structure on an outcrop of ball clay, so little attention has been paid by the author, or indeed the ball clay companies, to the geotechnical properties of the ball clays. Best and Fookes (1970) describe some of the geotechnical properties of the ball clays. The lack of a published detailed stratigraphy of the Bovey Basin prevented Best and Fookes from making other than very general but interesting conclusions.

The detailed stratigraphy was described in the main body of this thesis. Nine samples were collected from the two commercial members, on which some geotechnical tests were made by the Department of Civil Engineering, University of Surrey. It is with these tests and comparison with some of the other physical features of the ball clays that this Appendix is concerned.

A.5.2. Procedure.

Nine samples (numbered one to nine with no particular numerical significance) were taken. The first sample selected was of a brecciated ball clay, as described in the main body of the thesis. The originally
sampled lens of brecciated clay in the Carbonaceous part of the Abbrook Member had been worked out at the date of the later sampling, and a further example had to be located. A very similar lens of brecciated clay was located in the Upper Southacre and was accordingly sampled. Three other samples were taken from the Southacre Member, one from the Clay Facies at Chudleigh Knighton (Sample No. 3) and two from the Upper Southacre Member at Southacre Pit, one sample being very carbonaceous (Sample 5) and the other a silty slightly carbonaceous clay (Sample 8). The other five samples were from the Abbrook Member; two from underground working in the Carbonaceous part (Samples 2 & 4), two siliceous samples from different opencast localities (Samples 6 & 7), and the final one (Sample 9) of an apparently very plastic clay from just below the heading surface in a recently opened quarry.

Each sample was split into two parts, one part being sent to the University of Surrey for geotechnical tests, and one part being retained for other test work.

The retained samples were first tested for moisture, the tests being started within an hour of the samples being taken. To conform with general geotechnical practice, the moisture contents were calculated on the dry weight basis, rather than the wet weight basis as is commonly used in the clay industry. Hence values of moisture in the Appendix are relative but higher than those found in the general body of the thesis. Where possible, five moisture determinations were made, and a mean taken.

Other tests included chemical analysis (X.R.F.), X-Ray Diffraction and Particle Size Analysis (Natural and Ultimate).
Percent less than

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<th>Ultimate</th>
<th>Natural</th>
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<td>97</td>
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<tr>
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<td>56</td>
</tr>
<tr>
<td>1</td>
<td>54.5</td>
<td>46</td>
</tr>
</tbody>
</table>

Moisture Content on dry weight basis (%)
(21.6, 26.3, 26.1) Mean 24.7

SiO₂ 59.6% Loss-on-ignition 10.9%

Liquid Limit (W L) 52%
Plastic Limit (P L) 27%
Plasticity Index (I P) 26%
Liquidity Index (I L) 0.10
**Percent less than**

<table>
<thead>
<tr>
<th>Size (μm)</th>
<th>Natural</th>
<th>Ultimate</th>
</tr>
</thead>
<tbody>
<tr>
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<td>99</td>
</tr>
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<td>10</td>
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<td>97.5</td>
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<tr>
<td>5</td>
<td>82</td>
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<td>87</td>
</tr>
<tr>
<td>1</td>
<td>59</td>
<td>75</td>
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</tbody>
</table>

Moisture Content on dry weight basis (%)

(21.8, 21.7, 22.2, 19.4, 22.3) Mean 21.5

$\text{SiO}_2$ 49.5% Loss-on-ignition 12.9%

- Liquid Limit ($W_d$) 59%
- Plastic Limit ($P_l$) 29%
- Plasticity Index ($I_p$) 30%
- Liquidity Index ($I_L$) 0.25
Percent less than

<table>
<thead>
<tr>
<th>Size (µm)</th>
<th>Natural</th>
<th>Ultimate</th>
</tr>
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<tbody>
<tr>
<td>20</td>
<td>97.5</td>
<td>99</td>
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<td>96</td>
</tr>
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<td>85</td>
<td>88.5</td>
</tr>
<tr>
<td>2</td>
<td>65</td>
<td>68.5</td>
</tr>
<tr>
<td>1</td>
<td>52.5</td>
<td>55</td>
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</table>

Moisture Content on dry weight basis (%)

(18.0, 18.8, 16.8, 19.4, 17.8) Mean 18.1

SiO₂ 59.0%  Loss-on-ignition 9.4%

Liquid Limit (ωₗ)  48%
Plastic Limit (ωₚ)  24%
Plasticity Index (Iₚ)  24%
Liquidity Index (Iₗ)  -0.25
Percent less than | Natural | Ultimate
---|---|---
20µ | 95 | 99.5
10µ | 90 | 99
5µ | 83 | 96
2µ | 70 | 87.5
1µ | 57.5 | 78

Moisture Content on the dry weight (%)
(25.1, 25.9, 26.4, 28.3, 24.4) Mean 26.0

5102 45.3% Loss-on-ignition 17.8%

Liquid Limit (W_L) 63%
Plastic Liquid (P_L) 32%
Plasticity Index (I_p) 31%
Liquidity Index (I_L) 0.19

---

Fig. A.5.3.4. Very Carbonaceous Clay from the Abbrook Member.
Percent less than

<table>
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<th>Size (µm)</th>
<th>Natural</th>
<th>Ultimate</th>
</tr>
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<td>99</td>
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<td>97.5</td>
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<tr>
<td>5</td>
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<td>94.5</td>
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<tr>
<td>2</td>
<td>71</td>
<td>86</td>
</tr>
<tr>
<td>1</td>
<td>62</td>
<td>78</td>
</tr>
</tbody>
</table>

Moisture Content on the dry weight (%)

(25.5, 24.2, 24.8, 24.2, 24.6) Mean 24.7

SiO2 45.7% Loss-on-ignition 17.1%

Liquid Limit (Lw) 60%
Plastic Liquid (Pl) 36%
Plasticity Index (Ip) 24%
Liquidity Index (Il) 0.47

Fig. A.5.3.5. Very Carbonaceous Clay from the Southacre Member.
Percent less than Natural Ultimate

\[
\begin{array}{ccc}
20_{\mu} & e.s.d. & 96 & 97 \\
10_{\mu} & & 87 & 89 \\
5_{\mu} & & 75 & 76 \\
2_{\mu} & & 58 & 59 \\
1_{\mu} & & 46 & 51 \\
\end{array}
\]

Moisture Content on the dry weight (%)

\[
(12.1, 11.9, 11.5, 11.5, 11.2) \text{ Mean 11.6}
\]

SiO$_2$ 66.6% Loss-on-ignition 6.5%

Liquid Limit ($W_L$) 46%
Plastic Liquid ($P_L$) 18%
Plasticity Index ($I_p$) 28%
Liquidity Index ($I_p$) - 0.23

Fig. A.5.3.6. Very Silty Clay from the Abbrook Member.
Moisture Content on dry weight basis (\%) 
(12.0, 12.1, 12.0, 11.9, 11.8) Mean 12.0

$SiO_2$ 67.2% Loss-on-ignition 7.0

Liquid Limit ($W_L$) 35%
Plastic Limit ($W_P$) 15%
Plasticity Index ($I_P$) 20%
Liquidity Index ($I_L$) = 0.15

Percent Less than Ultimate

\begin{align*}
20_{\mu} & \text{ e.s.d.} & 88 \\
10_{\mu} & \text{ e.s.d.} & 79 \\
5_{\mu} & \text{ e.s.d.} & 66 \\
2_{\mu} & \text{ e.s.d.} & 54 \\
1_{\mu} & \text{ e.s.d.} & 48 \\
\end{align*}

Fig. A.B.3.7. Very Silicious Clay from the Abrook Member.
### Percent less than Natural Ultimate

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<tr>
<th>Size</th>
<th>Natural</th>
<th>Ultimate</th>
</tr>
</thead>
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<tr>
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<td>98.5</td>
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<tr>
<td>10 μm</td>
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<td>2 μm</td>
<td>57</td>
<td>61</td>
</tr>
<tr>
<td>1 μm</td>
<td>40</td>
<td>46.5</td>
</tr>
</tbody>
</table>

### Moisture Content on dry weight basis (%)

(17.7, 17.8, 17.4, 21.0, 17.2) Mean 18.2%

### SiO₂

56.8% Loss-on-ignition 9.4%

### Physical Properties

- **Liquid Limit (W_L)**: 47%
- **Plastic Limit (W_P)**: 26%
- **Plasticity Index (I_P)**: 21%
- **Liquidity Index (I_L)**: 0.37

---

**Fig. A.5.3.2.** Silty Carbonaceous Clay from the Southee Member.
Moisture Content on dry weight basis (%)
(17.7, 17.2, 16.6, 16.9, 17.0) Mean 17.1

SiO₂ 69.6% Loss-on-ignition 5.6%

Liquid Limit (W_L) 43%
Plastic Limit (W_P) 21%
Plasticity Index (I_p) 22%
Liquidity Index (I_L) - 0.18

Fig. A.5.3.9. Silty Clay from a recently opened quarry in the Abbrook Member.
The Department of Civil Engineering carried out tests for Liquid Limit \((W_L)\) and Plastic Limit \((W_p)\) from which the Plasticity Index \((I_p)\) could be calculated by simple subtraction.

Liquidity Index \((I_L)\) could then be computed from the moisture content \((W)\) and these latter parameters by the simple formula:

\[
I_L = \frac{W - W_p}{I_p}
\]

A.5.3. Results.

All the results are shown in Figs. A.5.3.1. to A.5.3.9. Each figure shows all the results for one sample, the final number in the Figure number referring to the sample number. Each figure includes the particle size analysis (Natural and Ultimate) in both curve and table form, the moisture (five determinations and the Mean), Silica and Loss-on-ignition values extracted from the Chemical Analyses, Liquid Limit, Plastic Limit, Plasticity Index, Liquidity Index, and the X-Ray Diffraction Trace with the Hickley Crystallinity Index calculated and shown. Correlation with free quartz calculated from the X.R.D. proved virtually identical to the correlation with \(SiO_2\) values, and free quartz values have not therefore been included.

A.5.4. Discussion of Moisture Content Results.

The previous work on moisture content, showed a good correlation with silica content, which was considered to reflect other factors such as particle size. In this case the variation in moisture contents can be compared with variation in particle size, crystallinity index of the kaolinite, and various chemical properties, of which \(SiO_2\) and Loss-on-ignition...
Fig. A.5.4. Variation of moisture content.
are considered to be of greatest relevance. The various plots of moisture content against these parameters are shown in Fig. A.5.4. Four of the particle size parameters could be selected for comparison, namely the $2\mu$ and $1\mu$ points of both Natural and Ultimate particle size distribution. In practice each point gives a similar pattern, but with slightly better definition on the $2\mu$ point of the Ultimate distribution, which was chosen therefore as the parameter to represent the variation in particle size. If the brecciated sample (No. 1) and the anomalous sample from immediately below the heading (No. 9) are discounted, the remaining seven samples show a good correlation of increasing moisture content with increasing fineness of the sediment.

Variation of moisture content with the Hinckley Crystallinity Index produces a more complex picture. There is certainly no apparent straightline relationship unless the two stratigraphic members are separated, then a trend of higher moisture content with decreasing crystallinity within each member can be recognised, although the Southacre Member shows equivalent moisture contents to the Abbrook Member for higher crystallinity.

Silica content reflects the amount of non-plastic quartz present in the sample, and as would be expected, shows a very clear trend of increasing moisture content with decreasing silica content, but again Samples 1 and 9 are anomalous, showing much higher moisture contents than would be expected from the percentage of silica.

The correlation of moisture content with Loss-on-ignition shows the opposite trend, with the highest moisture contents being recorded on samples with the largest Loss-on-ignition. The Loss-on-ignition reflects silica content and carbon content, the lower values representing
the most siliceous clays and the higher values the most carbonaceous, so this correlation indicates that moisture content tends to increase with increasing carbon. Again Samples 1 and 9 are anomalous, with higher values of moisture than would be expected from the Loss-on-ignition values. Sample 1 was a brecciated sample, with more siliceous pieces contained in a carbonaceous matrix, and the matrix obviously has the strongest influence on the moisture content. Sample 9 was taken from just below the heading in a newly opened quarry, and it is suspected that its comparatively coarse grain and proximity to the surface allowed re-introduction of moisture which could not occur in a finer clay.

A.5.5. Variation of Liquid Limit.

The variation of Liquid Limit with particle size, crystallinity index, silica and Loss-on-ignition is shown on Fig. A.5.5.

The trends are virtually identical with those of moisture content, showing increasing Liquid Limit with increasing fineness, with greater disorder (again separated from the two members and apparently on a curve rather than a straight line), with less silica and with more carbon. The highest Liquid Limit recorded was 63%, this sample (No. 4) being from the carbonaceous part of the Abbrook Member, with 87.5% less than 2μ, Hinckley Crystallinity Index of 0.15, Silica Content of 45.3% and Loss-on-ignition of 17.8. The lowest Liquid Limit recorded was 35%, on a very siliceous clay from the Abbrook Member (Sample No. 7), with 54% less than 2μ, crystallinity index of 0.30, silica content of 67.2% and Loss on ignition of 7.0% (the last being slightly anomalous).

Samples 1 and 9 are less anomalous than for moisture content, but have been joined in the slightly anomalous category by Sample 6, a very silty clay from the Abbrook Member.
Fig. A.5.5. Variation of Liquid Limit.
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A.5.6. **Variation of Plastic Limit.**

The variation in Plastic Limit with particle size, Hinckley Crystallinity Index, Silica and Loss-on-ignition, is shown on Fig. A.5.6.

The trends shown are identical to those shown for both moisture content and Plastic Limit. The Plastic Limit increases with increasing fineness, increasing disorder of the kaolinite (again on a curve), increasing carbon content, and decreasing silica content. The highest Plastic Limit recorded, 35%, was that of Sample 5 (a carbonaceous clay from the Southacre Member) which was 87% less than 2ν, Hinckley Crystallinity Index 0.22, Silica 45.7% and Loss-on-ignition 17.1%. The lowest value of 15% was again recorded on Sample 7 (64%, 0.30%, 67.2% and 7.0% respectively).

The most anomalous results were again recorded on Samples 1 and 9, but in this case, were joined by Sample 8 (Silty Carbonaceous Clay from the Southacre Member).

A.5.7. **Variation of Plasticity Index.**

The variation in Plasticity Index with the four chosen parameters is shown on Fig. A.5.7.

Although there is a great deal more scatter, the normal trends of increasing activity with finer particle size, greater disorder of kaolinite, higher carbon content and decreasing silica content can be recognised. As with the Liquid Limit, the highest value of Plasticity Index (31%) was recorded on Sample 4 (87.5% less than 2ν, 0.15 Crystallinity, 45.3% SiO₂ and Loss-on-ignition 17.8%). As with both Liquid and Plastic Limits, the lowest activity (20%) was recorded on Sample 7.
**Fig. A.5.6. Variation of Plastic Limit.**

- **% loss than 2 microns e.s.d.**
- **Hindley Crystallinity Index**
- **% SiO2**
- **% Loss on Ignition**

**Legend:**
- △ Southacre Member.
- ○ Abbrook Member.
Fig. A.5.7. Variation of Plasticity Index.

- Southacre Member.
- Abbrock Member.
The most anomalous results were recorded on Sample 5 (Carbonaceous Clay from the Southacre Member), and Sample 6 (Very Silty Clay from the Abbbrook Member).

Sample 5 had a very much lower activity than would be expected from its fine grained nature, from its degree of disorder, from its low silica content, and its high carbon content. The last mentioned parameter supplies the most likely answer. Carbon exists in two forms, one a very fine grained carbon and the other as "splatter" lignite. The fine grained carbon apparently increases the geotechnical values, but it is suggested that the "non-plastic" Lump lignite does not have the same effect, particularly when considering the Plasticity Index. Sample 5 contained more splatter lignite and lignitized twigs than any other of the samples, and this has probably had the effect of reducing the Plasticity Index in relation to each parameter.

Sample 6 has a much higher Plasticity Index than would be expected from its particle size distribution, silica and Loss-on-ignition values. This sample is a non-carbonaceous clay, so in this case, it is not the carbon which causes the apparent anomaly. Sample 6, however, does contain one of the highest alkali contents of all the samples \((K_2O + Na_2O 2.54)\), which reflects the amount of felspar, mica or interstratified mineral present. Felspar, however, is a non-plastic element, whilst mica and interstratified mineral would be expected to increase the values of the geotechnical properties of the sample. For this reason, correlation of geotechnical properties with alkali content produces little apparent correlation, although with some imagination a trend of increasing Plasticity Index with increasing alkali content can be dimly recognised. The X-Ray Diffraction trace on Sample 6 (See Fig. A.5.2.6.) shows the presence of felspar and mica in moderate quantities.
but no interstratified mineral can be detected. Unfortunately, mica and felspar cannot be quantified from X-Ray Diffraction, and correlation is therefore not possible, but the high Plasticity Index shown by Sample 6 is probably due to the presence of fine mica, which has tended to increase the Liquid Limit, whilst the felspar content has tended to depress the Plastic Limit slightly, thus widening the Plasticity Index.

A.5.8. Variation of Liquidity Index.

The variation on Liquidity Index ($I_L$) is shown in Fig. A.5.8. The trends of variation are more obscure than for the other properties, but since Liquidity Index is calculated from values all of which vary with lithology, it would be expected to find some degree of correlation. The graph of Liquidity Index against the Hinckley Crystallinity Index, however, shows no apparent correlation. Variation with the other parameters, however, do show trends, which are the reverse of the ones seen in the other geotechnical properties. Liquidity Index tends to decrease with increasing fineness and carbon content, and to increase with increasing silica content. Sample 5 (Carbonaceous Clay from the Southacre Member) showed the lowest Liquidity Index of $-0.47$ (86% less than the $2\mu, \text{SiO}_2$, 45.7%, Loss-on-ignition 17.1%). Sample 1 (Brecciated clay from the Southacre Member) showed the highest Liquidity Index of $-0.10$ (63% less the $2\mu, 59.5\% \text{SiO}_2, 10.9\% \text{Loss-on-ignition}$). Six of the nine Samples, however, were in the range $-0.15$ to $-0.25$. The lowest values were recorded on the three Southacre Member samples (excluding the brecciated Sample 1, which had a higher Liquidity Index by virtue of its anomalously high natural moisture content), these values being $-0.25$ (Sample 3), $-0.37$ (Sample 8) and $-0.47$ (Sample 5). These figures agree well with the values determined by Best and Fookes (1970), who recorded values of $-0.30$ to $-0.45$ on clays of the Southacre Member. The five samples from
Fig. A.5.B. Variation of Liquidity Index

Variation of Liquidity Index
the Abbrook Member show a range in value from -0.15 to -0.25. The stoneware clays tested by Best and Fookes, were from the Stover Member, and these show values of -0.16 to -0.25. The stratigraphic order of these three members, is that the Stover Member overlies the Southacre Member with a considerable unconformity (the Twinyeo Member being absent), and the Southacre Member overlies the Abbrook Member with a small discordance. Liquidity Index certainly indicates overconsolidation, but cannot indicate degree of overconsolidation due to overburden removal, because the lowest strata (the Abbrook Member) do not show the lowest Liquidity Indices. It could be argued that the Southacre Member has been subjected to greater disiccation, but there is no other evidence to support this premise.

The stoneware clays of the Stover Member are not dissimilar to some of the clays of the Abbrook Member, and it is suggested that secondary consolidation as suggested by Bjerrum (1967) on a geological time scale, has acted on the differing lithologies of the ball clays to produce the variations in Liquidity Index and the patterns of overconsolidation, and within that broad context that it is particle size and mineralogy, which control the final value of the Liquidity Index. For example, Sample 5, which shows the greatest apparent overconsolidation, also had an anomalously low Plasticity Index. Division of a negative number by a small number produces a lower negative number than division by a larger number, hence division by the lower Plasticity Index apparently indicates a higher degree of overconsolidation.

Samples 2 and 4 from the Abbrook Member showed the greatest anomalies when plotting Liquidity Index against the various parameters.
These two samples, however, were the most active of all the samples (Plasticity Indices of 30 and 31 respectively), and division of a negative number by a larger number produces a higher negative number. Hence, Liquidity Index is very dependant upon the activity of the clay, which has been shown to be dependant on lithology.

A.5.9. Summary and Conclusions:

1. Moisture content increases with decreasing particle size. Individually within the Southacre and Abbrook Members there is a trend of higher moisture content with greater disorder of the kaolinite. Moisture content decreases with increasing silica, and increases with a higher carbon content. The brecciated sample and the apparently very plastic sample proved to give anomalous values.

2. Liquid Limit and Plastic Limit increase with increasing fineness, greater disorder of the kaolinite and higher carbon content and decreases with increasing silica content.

3. Plasticity Index varies in a similar manner, but with some scatter due to variation in the form of carbon present and to the quantities of mica, felspar and interstratified mineral present.

4. The variation in Liquid Limit is considered to show that secondary consolidation on a geological time scale has produced varying degrees of overconsolidation depending upon the lithology of the ball clay.

5. The Geotechnical Properties of the ball clays depend largely upon the lithology of the sediment.
Fig. 6.2 The Geology of the Bovey Basin

SCALE: 1/25000
Fig. 6.3 Variation in the Southacre and Abbrook Members along the Eastern outcrop of the Bovey Basin

- Clay: Vertical Scale 1:500
- Sand: Horizontal Scale 5 inches to 1 mile (1:10,000 Approx.)
- Lignite
- Unconformity