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Title: A British Pleistocene chronology based on uranium series and electron spin resonance dating of speleothem.
A BRITISH PLEISTOCENE CHRONOLOGY BASED ON URANIUM SERIES
AND ELECTRON SPIN RESONANCE DATING OF SPELEOTHEM.

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ABSTRACT.

Considerable progress has been made in recent years towards constructing a British Pleistocene stratigraphy. However this sequence has yet to be satisfactorily dated and correlated with long climatic records such as the marine oxygen isotope chronology. This thesis aims to use the dating of speleothems associated with mammal faunas and marine transgressive sediments in caves, to provide a dated framework for the British Middle and Upper Pleistocene sequence and permit correlation with the marine oxygen isotope record.

Cave deposits with Middle Pleistocene mammal faunas and Lower Palaeolithic industries were dated at Kent’s Cavern, Devon, and Three Holes Cave and Tornewton Cave in the Torbryan valley, Devon. Devensian mammal faunas were dated in Minchin Hole, Gower, Kent’s Cavern, Devon, and Rhinoceros Hole, Mendip: Middle to Upper Palaeolithic industries were also present in all these sites except Minchin Hole.

Middle and Upper Pleistocene raised beaches were dated at Minchin Hole, Gower, and Saddle Head Cave, Pembroke. A longer Middle to Upper Pleistocene marine transgressive record was obtained from ponding sediments in the Berry Head caves, Devon.

These results are discussed and combined with those of other workers to arrive at possible chronological schemes for the British Middle and Upper Pleistocene. The preferred scheme (chronology A) features a sequence of four post-Cromerian interglacials with marine transgressions, correlated with oxygen isotope stages 11, 9, 7 and 5e. The Anglian Glaciation is correlated with stage 10. Within the Devensian a sequence of three interstadials (the first two with woodland and warm faunas) are tentatively identified with stages 5c, 5a and 3. A possible alternative scheme for the Middle Pleistocene (chronology B) differs in having a sequence of 5 post-Cromerian interglacials correlated with oxygen isotope stages 13, 11, 9, 7 and 5e, and a correlation of the Anglian Glaciation with stage 12.
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I am indebted to the following people for help in dating work. Martin Broderick helped train me in uranium series dating techniques. Nick Debenham arranged for me to use the British Museum TL laboratory and showed me how to make TL measurements. Ian Podmore and Martyn Symons carried out ESR spectrometry on samples from Kent's Cavern and Tornewton Cave. Andy Baker dated two samples from Kent's Cavern.

Technical, cartographic and photographic support at Bristol was provided by Dave King, Richard Newman, Simon Godden and Tony Philpott. Technical support at Exeter was provided by Art Ames.

This thesis is dedicated to my wife Janet, who saw far more of the fieldwork sites than she probably wished to, and suggested it be called 'The Albatross'.
This thesis is the original work of the candidate except where acknowledgement is given, and has not been submitted for a higher degree in this or any other University.

Christopher John Proctor

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1. INTRODUCTION.

1.1. The British Pleistocene chronology.

The early work on the British Pleistocene chronology used as its stratigraphic base four glacial periods (the Gunz, Mindel, Riss and Wurm glaciations) established in the Alps by Penck and Bruckner (1901/1909) at the turn of the century, and later elaborated and extended for Western Europe by Woldstedt (1958). The use of this stratigraphic framework in British Pleistocene research was made difficult by the problems of fitting the British evidence into a scheme established in an area many hundreds of miles away, and in 1973 an alternative stratigraphy based on the British sequence was published (Mitchell et al. 1973). They employed a sequence of three glaciations (the Anglian, Wolstonian and Devensian) and two interglacials (the Hoxnian and Ipswichian) after the Cromerian Interglacial period, some 400 to 500 ka (thousand years) ago (fig. 1.1). This chronology was based upon the observed relationships between Pleistocene sediments in the British Isles (mainly S.E. England), and was heavily dependant on the use of palynology to correlate and establish a chronology for widely separated interglacial deposits.

In the same year Shackleton and Opdyke (1973) published a palaeomagnetically dated 870 ka record of variations in $^{18}O$/$^{16}O$ ratios in deep sea core V28-238 (fig. 1.1). They
Figure 1.1.

(a) The British Pleistocene stratigraphy of Mitchell et al. (1973).

(b) The marine oxygen isotope record, showing a much more complex sequence of climatic fluctuations (Shackleton and Opdyke 1973).
argued that the variations in the $^{18}O$/$^{16}O$ ratio resulted from changes in global ice volume and that the oxygen isotope record also provided a proxy record of Pleistocene sea level variations and climate, since both are closely related to global ice volume. Since then the oxygen isotope record has been considerably refined, particularly by the use of orbital tuning to produce an improved chronology for the record (Imbrie et al. 1984, Martinson et al. 1987).

Support for this interpretation of the oxygen isotope record has been provided by dating coral reef terraces deposited at times of high sea level (Bloom et al. 1974, Edwards et al. 1987, Smart and Richards 1992, Gallup et al. 1994) which show the pattern of marine transgressions predicted by the oxygen isotope record and confirm the validity of the orbital tuning dating method. More detail is provided over the last interglacial-glacial sequence, by other climatic records such as the long pollen sequences obtained from Grande Pile, France (Woillard 1978). These have been used to derive detailed temperature and precipitation histories (Guizot et al. 1989) by comparison with the present day climatic tolerances of the flora, although more recent work using both pollen and beetles raises doubts about the reliability of this approach (Guizot et al. 1993). Ice core records from the Greenland ice cap have recently yielded very high resolution data on climate in the last two interglacial-glacial cycles (GRIP members 1993, Dansgaard et al. 1993,
Taylor et al. 1993a), although there are problems with the lower part of these records due to ice shear (Taylor et al. 1993b, Grootes et al. 1993). Both the long pollen record and the ice core records are more detailed than the oxygen isotope record, and show a more complex climatic history. However in general they correlate well with it, confirming the interpretation placed on the oxygen isotope record by Shackleton and Opdyke (1973).

A continental oxygen isotope climatic record is provided by vein calcite in Devils Hole, Nevada (Winograd et al. 1992, Ludwig et al. 1992). This record is of particular importance for two reasons: its long range of 500 ka back from the present, and because it has been directly dated to high precision by mass spectrometric U-series analysis of the calcite. Over much of its range the Devils Hole record shows a good agreement with the marine oxygen isotope record. However, Winograd et al. (1992) note that the Devils Hole record places the stage 7 and 5 deglaciations significantly earlier, and use these results to cast doubt upon the chronology of the marine oxygen isotope record. This claim has attracted controversy both regarding the dating of the Devils Hole record, and Winograd et al.'s (1992) interpretation of it (Edwards and Gallup 1993, Imbrie et al. 1993, Shackleton 1993): further results are needed to resolve this dispute. In view of the good match between the marine oxygen isotope and Devils Hole records over most of the time range covered, it seems unlikely that the dating of
the marine record is fundamentally wrong: however it may be that Devils Hole is showing us that the controls on Pleistocene climatic change are more complex than previously thought. The marine oxygen isotope record (Imbrie et al. 1984, Martinson et al. 1987) is retained here as providing probably the best established currently available chronology of Pleistocene climatic change.

The oxygen isotope record shows a highly complex sequence of climatic oscillations with five major glacial-interglacial cycles over the past 500 ka, in contrast to the formal stratigraphy for Britain (Mitchell et al. 1973), which postulates a much simpler climatic record with less frequent glacial-interglacial cycles. In addition the oxygen isotope record shows that each interglacial period may have been very complex, with several fluctuations between warmer and cooler conditions, again in contrast to the simple sequences of climatic amelioration followed by decline into the next glaciation postulated in the pollen based formal stratigraphy. Clearly the stratigraphy of Mitchell et al. (1973) cannot be reconciled with the evidence provided by the oxygen isotope record.

Independant evidence for a greater number of interglacial-glacial cycles in the British Pleistocene than was recognised in the formal stratigraphy is provided by the changing mammal faunas. Sutcliffe and Kowalski (1976) utilised the rapid rate of evolution of
small rodents in the Middle and Upper Pleistocene to construct a biostratigraphic framework for the period. They pointed out that there was good faunal and stratigraphic evidence at sites in the Thames valley for a previously unrecognised interglacial (here called the Aveley Interglacial; see below) predating the Ipswichian Interglacial but postdating the Hoxnian Interglacial. They also supported Bishop's (1975) proposal that a fauna at Westbury-sub-Mendip dated from a second previously unrecognised warm period, the 'Westbury sub stage', post-Cromerian but pre-Hoxnian in age. This basic sequence has been refined by later workers, in particular Currant (1989) who has recognised a series of five full interglacial faunas, each with a distinctive mammalian assemblage, since the Cromerian (fig. 1.2). Independant support for this mammalian chronology has been provided by the amino acid racemisation work of Bowen et al. (1989), which shows that the interglacial sites referred by Sutcliffe and Kowalski (1976) to the pre-Ipswichian (Aveley) interglacial are indeed intermediate in age between the Hoxnian and the Ipswichian, confirming the existence of this interglacial.

Another major advance has been the recognition of faunas dating from the end of the Ipswichian Interglacial at Bacon and Minchin Holes, Gower (Sutcliffe and Currant 1984, Stringer et al. 1986). These document a sequence of complex climatic and faunal changes, with interglacial type faunas persisting well into the early Devensian, and
Figure 1.2.

The interglacial mammal stratigraphy (a) and correlations with the marine oxygen isotope record (b). Correlations (c) have been made by radiometric dating of deposits at mammal sites (Gascoyne et al. 1981, Green et al. 1981, Green et al. 1984, Sutcliffe et al. 1985, Stringer et al. 1985).
are of significance for two main reasons. Firstly they show that warm conditions occurred over much longer periods than previously thought. Secondly the 'warm' faunas occur interbedded with faunas of 'cold' type and provide the first evidence in Britain for complex climatic oscillations within a warm period. These findings are consistent with the oxygen isotope record, which shows that the warm periods were of extended duration and included complex climatic oscillations, rather than with the formal stratigraphy, which postulates short simple interglacials punctuating a generally cold climate. The mammal chronology discussed above is summarised in fig. 1.2.

Clearly, the above evidence implies that the formal stratigraphy of Mitchell et al. (1973) is in need of drastic revision. For convenience of discussion their interglacial names are retained in this thesis, with the addition of the names 'Westbury Interglacial' and 'Aveley Interglacial' for the post-Cromerian and pre-Ipswichian Interglacials respectively (the Aveley Interglacial is named after a site with a well preserved fauna of this age). It should be noted that the latter two interglacial names have no validity outside the context of this thesis. The timing and indeed the existence of the Wolstonian Glaciation is at present a matter for debate (Shotton 1986, Rose 1989), and no attempt is made to incorporate it into the chronology presented here. The Anglian Glaciation is placed between the Westbury and
Hoxnian Interglacials, after Bishop (1982) (fig. 1.2), although it is by no means certain that all 'Anglian' deposits can be referred to this interval.

Two main approaches have been used to attempt correlation of the British terrestrial sequence with the oxygen isotope record. The first is to directly date terrestrial sites for comparison with the dated oxygen isotope record. Some progress has been made in dating the last interglacial mammal faunas by application of the uranium series technique on associated speleothem on cave deposits. The Ipswichian *Hippopotamus* fauna has been dated to around 120 ka (Gascoyne et al. 1981), permitting correlation of the Ipswichian Interglacial with stage 5e of the oxygen isotope record. At Bacon Hole, Gower, faunas dating from the end of the last interglacial complex, which retain some 'interglacial' species, have been dated to between 81±18 and around 125 ka, rather later in stage 5 (Stringer et al. 1986). A dated fauna with *Gulo* (wolverine) and *Rangifer* (reindeer) at Stump Cross Cave, Yorkshire, suggests that by 83±6 ka the 'interglacial' faunas had been replaced by a cold fauna similar to those that occurred through the rest of the Devensian (Sutcliffe et al. 1985). Further work is required to refine our knowledge of faunal change over this period. A number of Devensian faunas have been dated, demonstrating the relatively unchanging nature of the mammal faunas through this period, but little progress has been made in dating faunas predating the
lpswichian. A temperate fauna at Marsworth, thought to represent an interstadial between the Aveley and Ipswichian Interglacials, has been dated to between 140 and 170 ka by uranium series dating of associated tufa (Green et al. 1984). A further Middle Pleistocene deposit at Pontnewydd Cave, dated to oxygen isotope stage 7 (Green et al. 1981, Currant 1984, Schwarcz 1984), is of considerable archaeological significance but not so helpful in the faunal context. Unfortunately the rather sparse fauna could be referred to either the Aveley or the Hoxnian Interglacial with equal ease. These correlations with the oxygen isotope record are summarised in figure 1.2.

The second method for correlation of the terrestrial and marine records relies upon the record of glaciations, which are represented by widely distributed tills (in contrast to the scattered interglacial deposits) and thus provide good lithostratigraphic marker horizons. In particular the Anglian Glaciation has been correlated with oxygen isotope stage 12, which appears to be the most severe cold phase in the Middle Pleistocene oxygen isotope record (Bowen et al. 1986a, Shackleton 1987). This approach is less rigorous than direct dating, since it assumes that the maximum glaciation will have coincided with the deepest dip in the oxygen isotope curve, which may not necessarily be true. However it provides a starting point from which a testable chronology can be developed. This correlation has been combined with the
dating results (see above) and aminostratigraphy of post-Anglian interglacial sites by Bowen et al. (1986a, 1989) to produce the sequence shown in fig. 1.3. This sequence further subdivides the interglacials recognised by Sutcliffe and Kowalski (1976) and Currant (1989), by dividing the Hoxnian sites into two interglacials correlated with oxygen isotope stages 9 and 11. The chronology of Bowen et al. (1989) is accepted by many workers as the best current model of the British terrestrial Pleistocene stratigraphy. However it is not without problems. In particular, the Westbury Interglacial is not recognised, even though its existence as a distinct interglacial is fairly well established (Andrews 1990).

Another approach to constructing a British Middle and Upper Pleistocene chronology is by using the record of marine transgressions, which mark the occurrence of full interglacial conditions. Early work on raised beaches was beset by problems of dating and correlation, but these have now been to some extent overcome. Sutcliffe (1985) used estuarine terraces of the Thames with incorporated mammal faunas to infer marine transgressions to slightly higher than at present during the Ipswichian, 6 m above present during the Aveley Interglacial, and 25 m above present in the Hoxnian Interglacial. Using a similar logic, a transgression to around 40 m above present during the Westbury Interglacial can be inferred from the Goodwood Beach at Boxgrove in Sussex, which has rodents
<table>
<thead>
<tr>
<th>OXYGEN ISOTOPE STAGE</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Holocene</td>
</tr>
<tr>
<td>2-4</td>
<td>Devensian Glaciation</td>
</tr>
<tr>
<td>5</td>
<td>Ipswichian Interglacial</td>
</tr>
<tr>
<td>6</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Stanton Harcourt (=Aveley Interglacial of this thesis)</td>
</tr>
<tr>
<td>8</td>
<td>Paviland Glaciation</td>
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<tr>
<td>9</td>
<td>Hoxnian Interglacial (= part of Hoxnian Interglacial of this thesis)</td>
</tr>
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<td>10</td>
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<tr>
<td>11</td>
<td>Swanscombe (= part of Hoxnian Interglacial of this thesis)</td>
</tr>
<tr>
<td>12</td>
<td>Anglian Glaciation</td>
</tr>
<tr>
<td>13</td>
<td>Cromerian Interglacial</td>
</tr>
</tbody>
</table>

Figure 1.3.
A scheme for the post-Cromerian Pleistocene sequence, from Bowen et al. (1986a), Bowen et al. (1989).
characteristic of this interglacial closely associated with it (Roberts 1986).

By contrast, the raised beaches of S.W. Britain generally have no associated mammals or pollen and their chronology has been worked out by the use of amino acid geochronology. Davies (1985) recognised four aminogroups (3 to 6) suggesting that beaches deposited by four separate marine transgressions could be recognised. Beaches correlated by Davies (1985) to aminogroup 3 have been dated by uranium series analysis of associated speleothem to around 125 ka at Minchin and Bacon Holes, Gower (Sutcliffe et al. 1987), and Belle Hougue Cave, Jersey (Keen et al. 1981), showing that they were deposited during isotope stage 5e (the Ipswichian Interglacial). Davies (1985) used the known age of these beaches to suggest on the basis of isoleucine epimerisation kinetics that her aminogroups 4, 5 and 6 corresponded to marine transgressions during oxygen isotope stages 7, 9 and 11 or 13 respectively. The only site referred by Davies to aminogroup 6 was the Goodwood beach, which as we have seen can be referred to the Westbury Interglacial. The temptation is to correlate aminogroups 4 and 5 to the Aveley and Hoxnian Interglacials and this is to some extent supported by comparison of the data of Davies (1985) and Bowen et al. (1989): however, further work is necessary before these correlations can be made with any confidence.
The later part of Davies' chronology was elaborated by Bowen et al. (1986b) who renamed her aminogroups 3 and 4 the 'Pennard' and 'Minchin' stages. They also proposed a third 'Unnamed' stage, intermediate in age between the other two stages, although its existence is disputed by Mottershead et al. (1987). Bowen et al. (1986b) ignored between-site temperature differences, but Hollin et al. (1993) suggest that these are sufficiently great to necessitate revision of Bowen et al.'s chronology, although they still retain the model of three distinct aminogroups.

1.2. This thesis.

1.2.1. Rationale.

While considerable progress has been made in unravelling the complexities of the terrestrial Pleistocene record in Britain, it is clear that correlation of this chronology with the deep sea oxygen isotope record has yet to be firmly established. Given the lack of distinctive marker horizons common to both records over the period concerned, the best way to securely correlate the terrestrial chronology with the oxygen isotope record is to obtain numerical age estimates for terrestrial sites which can then be compared to the dated oxygen isotope record.
Relatively few reliable dating techniques are available for the Upper and Middle Pleistocene beyond the range of $^{14}C$ dating (see Methods, below). Although the Pleistocene stratigraphy has largely been elucidated at open sites, these present severe problems for dating since they are generally devoid of suitable material. By contrast caves offer a high potential for yielding accurate results. This is because they are sites for deposition of calcite speleothems which are suitable for dating by a variety of techniques, particularly uranium series, ESR and TL methods (see Methods, below).

The study of Pleistocene sediments in caves has traditionally focussed on entrance facies deposits which are often rich in faunal and archaeological remains (Rosenfeld 1964b. Laville 1976). However, deep cave deposits are of considerable importance, for several reasons. Firstly, clean speleothem suitable for dating purposes grows in deep cave settings, that in near entrance environments generally being much more porous and often contaminated with clastic material. Thus deep cave environments offer better potential for high quality dating work. Secondly, they may preserve an environmental record that is considerably more durable than equivalent entrance facies or surface sediments. For instance, sediments within the caves may preserve a record of fluctuations in sedimentation rate or the water table that can be related to changes in conditions outside. The speleothems themselves preserve a valuable climatic
record since they grow mainly during warm periods and analysis of a large number of samples can be used to construct a proxy climatic record (Gordon et al. 1989, Baker et al. 1993).

Of particular significance is the inner end of entrance facies deposits, where sediment such as raised beaches, or with mammal faunas and archaeological remains may interfinger with deep cave deposits containing speleothems suitable for dating. Such sites combine the presence of stratigraphically distinctive material and dateable speleothem: they offer some of the best potential for useful dating work in elucidating the Pleistocene chronology. The potential of such an approach is illustrated by the successful dating of mammal faunas described above, such as Gascoyne et al. (1981), Green et al. (1981) and Stringer et al. (1986).

This thesis attempts to use speleothem dating in caves to provide a dated framework for the British Pleistocene sequence. In using this approach to date the British Pleistocene, the record of the glacial periods offers little hope of yielding useful data. There is considerable uncertainty about how many glaciations occurred, and where in the chronology they should be placed. In addition glaciations are not individually distinctive; there is no reliable way of correlating widely separated tills dating from the same glaciation. By contrast, the records of interglacial mammal faunas
and of interglacial marine transgressions are particularly amenable to this approach. Both records provide a sequence of distinctive events through the Middle and Upper Pleistocene, and mammal faunas and marine sediments occur in caves interstratified with dateable speleothem.

1.2.2. Available sites.

To carry out the work proposed above, it is clearly necessary to have access to sites where Middle and Upper Pleistocene sediments occur in caves. S.W. Britain is a particularly suitable region for this approach to deriving the chronology for a number of reasons. Numerous caves with Pleistocene deposits occur in the karst areas of Mendip, S. Wales, and Devon. In these areas cave deposits containing Pleistocene mammal faunas have long been known (reviews are given by Sutcliffe 1969, Sutcliffe and Kowalski 1976, Hawkins and Tratman 1977, Stuart 1983, Sutcliffe 1985, Davies 1989a, 1989b). The region has been little glaciated, and in comparison with the glaciated areas of the north, cave entrance deposits containing early mammal faunas are much more likely to have been preserved. In addition faunas dating from the periods of the glaciations may occur. Coastal caves occur in Devon and S. Wales, many of them demonstrably dating back to at least the Middle Pleistocene, providing sites where the raised beach chronology may be dated. The lack
of glaciation in the region is advantageous in interpreting the sea level history, since the problems of glacial isostasy are less than in other areas of Britain.

The constraints placed upon site selection by the requirements of dating, together with the relative scarcity of Pleistocene cave deposits containing mammal faunas, considerably restricts the choice of sites for this research. In addition, some sites have already been, or are being, satisfactorily dated, or the potential for dating has been destroyed by excavation and in extreme cases the total destruction of the site. Having taken these factors into account, the number of sites currently available in which useful work can be carried out is limited. The sites in which work was carried out are shown in fig. 1.4, and their potential significance is briefly outlined below.

(a) The terrestrial chronology.

(a.i) The pre-Ipswichian chronology.

(1) Kent's Cavern, Devon (chapter 4): the Breccia deposit contains a fauna including Ursus cf. deningeri, Pitymys gregaloides and Arvicola cantiana (Campbell and Sampson 1971, M.J.Bishop pers comm), which permits its approximate correlation with the Westbury Interglacial. In addition the Breccia has yielded a large number of
Figure 1.4.

Stratigraphic ranges of sites used in this thesis.

(a) Caves with mammal faunas.

(b) Caves with marine transgressive sediments.
crude Acheulian (Lower Palaeolithic) tools. Thus this site offers the potential for dating an early Lower Palaeolithic assemblage, and for obtaining an indication of the age of the Westbury Interglacial.

(2) Torbryan Caves, Devon (chapter 5): two sites in the Torbryan valley contain sediments with pre-Ipswichian faunas. Tornewton Cave has a very long faunal sequence from the Holocene to before the Ipswichian (Sutcliffe and Zeuner 1962). It is of particular importance as the only cave site with Crocidura, which is characteristic of the Aveley Interglacial, and thus holds the possibility of dating this interglacial. Three Holes Cave has a much sparser fauna but Lower Palaeolithic implements have been found in the lowest sediments (Colcutt 1985), which contain bones of a speleoid bear, showing them to be pre-Ipswichian in age. These sites are close together and show a number of similarities in their sequences, raising the possibility of correlation between them: they are best studied as a unit.

It will be noted that no sites with proven Hoxnian faunas were available, although a possible Hoxnian site exists in Sun Hole, Mendip, which has yielded the (Hoxnian?) snail Lyrodiscus (Ellis 1983).
(1) Minchin Hole, Gower (chapter 7): this coastal cave preserves deposits with 'warm' faunas dating from late in isotope stage 5. Minchin Hole and the nearby Bacon Hole are the only sites in Britain where distinct faunas of this period have been recognised, and further dating refines our knowledge of the timing of faunal changes at the end of the last interglacial complex (Stringer et al. 1986, Sutcliffe and Currant 1984). The transition from 'warm' to 'cold' faunas may not be preserved here (the overlying cold faunas are undated and may be from much later in the Devensian), but improved dating of the youngest 'warm' faunas helps to constrain the age of the transition when compared to other sites.

(2) Kent's Cavern, Devon (chapter 4): the Cave Earth preserves a long sequence of faunas and Middle and Upper Palaeolithic occupation horizons extending back from the Late-Glacial to at least the mid-Devensian (Campbell and Sampson 1971). The upper part of this sequence has been ¹⁴C dated, and dating of the base of the sequence is useful in constraining the age of the included faunas and occupation horizons, and particularly the Middle Palaeolithic occupation. In addition, by dating the start of deposition of the 'cold' faunas of the cave earth, the date of the transition from 'warm' to 'cold' faunas at the end of the last interglacial complex may be further constrained.
(3) Rhinoceros Hole, Mendip (chapter 6): a sequence of Middle to Upper Devensian faunas is preserved here, with Middle and Early Upper Palaeolithic industries.

(b) The sea level chronology.

(1) Berry Head Caves, Devon (chapter 3): a coastal phreatic system dating back to at least the Middle Pleistocene, containing sediments deposited by several Pleistocene marine transgressions. These deposits are useful both in dating the age of transgressions and in constraining the height reached by the sea at other times (e.g. late stage 5).

(2) Minchin Hole, Gower (chapter 7): beneath the late stage 5 faunal horizons (see above) is a sequence of two late Middle to Upper Pleistocene raised beaches. Aminostratigraphy of the beaches was carried out by Davies (1983) and Bowen et al. (1986): thus this site is important in dating their aminostages.

1.2.3. Structure of this thesis.

The methods used to carry out this work are briefly outlined in chapter 2 (Methods). Each of the following 5 chapters deals with one of the major sites, describing
work carried out and discussing those aspects of the interpretation which are relevant to that site or local problems of Pleistocene stratigraphy and chronology. The application of the results to the general British chronology are covered in chapter 9 (Discussion), and the conclusions set out in chapter 10.
2. METHODS.

2.1. Dating methods.

2.1.1. Available methods.

The available methods for dating Middle and Upper Pleistocene materials have been reviewed by Colman et al. (1987) and Smart (1991a). They classified dating methods into two schemes defining (a) the type of result produced (b) the type of method.

The type of result produced is classified as follows:

(a) Numerical age methods, producing quantitative age estimates, e.g. in years.

(b) Calibrated age methods, measuring changes which may depend on other variables which must be calibrated before an age can be obtained.

(c) Relative age methods give an indication of the relative ages of a series of samples (which is older or younger) but cannot produce a precise age.

(d) Correlated age methods provide evidence of equivalence (similar age of two sites or samples) but no age.
This research required the use of numerical dating methods. The following types of dating method are able to do this.

(a) Sidereal methods, using annual markers, e.g. dendrochronology, varve chronology. With rare exceptions sidereal methods are not applicable below the uppermost Pleistocene since it is necessary to have a datum of known age from which to count back (usually the present day, e.g. in dendrochronology).

(b) Radiometric (isotopic) methods, utilising the rate of decay of radioactive elements. This is constant and independant of environment, so can be used to provide a precise geochemical 'clock'. Three methods are generally used in the Middle and Upper Pleistocene:

(i) Radiocarbon (¹⁴C), applicable to a wide range of biological materials: limits 0.3 to 45 ka.

(ii) Potassium-Argon (K-Ar), limits 30 to 20,000 ka, but only applicable to volcanic rocks.

(iii) Uranium series (U-series), applicable to a wide range of materials, time range 3 to 350 ka.

(c) Radiogenic methods, measuring the cumulative non-isotopic effects of radioactive decay. The rate of change depends on the local radiation environment which must be
calibrated before an age is obtained. Thus dating depends on the accurate determination of two variables, and is less reliable than radiometric dating. The principle techniques are:

(i) Fission Track, range, 50 to 2000 ka, applicable to volcanic rocks.

(ii) Thermoluminescence (TL), applicable to a wide range of materials, range 0.1 to 500 ka.

(iii) Electron Spin resonance (ESR), applicable to a wide range of materials, range 5-900 ka.

Sidereal methods are not considered further because of their very limited applicability. Turning to radiometric methods, \(^{14}\)C dating has been used to great effect in producing a chronology of the Middle and Upper Devensian back to around 40 ka, but is of no use further back. The absence of volcanic rocks in the British Pleistocene precludes the use of K-Ar dating, so the only radiometric technique generally available for dating beyond the limit of \(^{14}\)C dating, is U-series. Of the radiogenic methods, fission track dating suffers from the same problem as the K-Ar method, a lack of volcanic rocks in Britain. TL and ESR dating have both been used in the time range concerned and have given reasonable results, though as noted above they are not able to match the precision or accuracy of radiometric techniques. Thus the principle
dating techniques capable of yielding numerical age estimates for the British Middle and Upper Pleistocene (beyond the 45 ka limit of \(^{14}C\)) are the U-series, TL and ESR methods.

This research uses two methods, uranium series and ESR dating. Uranium series dating is a well established and reliable technique and is probably the best available at present for the relevant time range. It is particularly suited to dating of carbonate materials such as speleothem in caves (see below) although a range of other materials may also be dated with difficulty. Thus it is ideal for this research since as noted above mammal faunas and sea level deposits can be located in association with datable speleothem in caves. This method was used at most sites. Electron spin resonance dating can also be used to date speleothem but due to its lower precision was only used where problems of age or detrital contamination made U-series dating inappropriate.

2.1.2. Uranium series dating.

Uranium series dating is a radiometric technique utilising the radioactive decay of naturally occurring isotopes of uranium. In the dating of carbonates, the decay of uranium into thorium provides the most useful dating method. Uranium-thorium dating has proved to be a reliable method for dating speleothem, and is extensively
used for the dating of such material. The technique is
described in detail by Schwarcz (1980, 1989): other U-
series methods are reviewed by Smart (1991b). Uranium-
thorium dating utilises the $^{238}$U decay chain. This
isotope is the most abundant naturally occurring isotope
of uranium, and decays with a half life of $4.49 \times 10^9$
years, via a series of daughter isotopes ending in the
stable isotope $^{208}$Pb (fig. 2.1). The isotopes used in
dating are $^{238}$U, $^{234}$U, and $^{230}$Th.

In undisturbed natural systems the activity ratios of the
various daughter isotopes will tend towards secular
equilibrium where they all exhibit the same activity
(rate of decay), e.g. each element decays as fast as it
is formed by the decay of the preceding element. At
secular equilibrium the activity ratios of any pair of
elements will be one since each exhibits the same number
of decays per unit time.

A system in secular equilibrium does not change with time
and thus offers no potential for dating. However, if the
decay chain is broken, (e.g. by chemical removal of one
of the isotopes) then a state of disequilibrium results.
For uranium and thorium this occurs because uranium is
readily dissolved in groundwater, and can be precipitated
in chemical sediments such as speleothem. By contrast
thorium is strongly adsorbed onto clays and hydroxides,
and is present in negligible amounts in groundwaters.
Thus the speleothem will initially contain appreciable
Figure 2.1.

The $^{238}\text{U}$ decay chain. The isotopes used in uranium-thorium dating are boxed. (After Gascoyne et al. 1976).

Figure 2.2.

Isochron plot of $^{234}\text{U}/^{238}\text{U}$ against $^{230}\text{Th}/^{234}\text{U}$ for a closed system initially containing no $^{230}\text{Th}$. Solid lines are isochrons: dashed lines show the change of isotope ratios with time. (After Gascoyne et al. 1978, Schwarcz 1980).
quantities of uranium but no thorium. Over time, decay of the uranium produces thorium, which increases in quantity until it reaches secular equilibrium. Since $^{238}$U has a very long half life the quantity present stays effectively constant, and the time taken to reach secular equilibrium depends primarily on the half life of the thorium isotope $^{230}$Th (7.52x10$^4$ years). It is also dependant on the activity ratio of the two uranium isotopes which are often slightly out of equilibrium when the sediment is initially deposited.

Thus to date a sample it is necessary to measure two ratios, $^{234}$U/$^{238}$U and $^{230}$Th/$^{234}$U. Armed with these it is then possible to calculate the age using the equation:

$$(^{230}\text{Th}/^{234}\text{U})_t = (^{238}\text{U}/^{234}\text{U})_0 \cdot (1 - \exp(-\lambda_{230} t)) + \lambda_{230}/\lambda_{230}\cdot\lambda_{234} \cdot (1 - (^{238}\text{U}/^{234}\text{U})_0 \cdot (1 - \exp((\lambda_{234}-\lambda_{230}) t)))$$

where:

$t$=age of the sample

$\lambda_{238}, \lambda_{234}, \lambda_{230}$ = activity constants for $^{238}$U, $^{234}$U, and $^{230}$Th.

(from Schwarcz 1980).

The change of the activity ratios of $^{234}$U/$^{238}$U and $^{230}$Th/$^{234}$U with time is shown in fig. 2.2. The $^{230}$Th/$^{234}$U ratio approaches unity (secular equilibrium) after about
350 ka and this determines the upper age limit of the method.

In order to produce a reliable age estimate, two criteria must be satisfied (Smart 1991b).

(a) The sample should initially contain no $^{230}$Th (i.e. at time of deposition).

(b) The sample should remain closed with respect to the isotopes involved in the dating process: that is, it should neither gain nor lose these elements by migration after the deposition of the sample.

Clean, massive speleothem carbonates meet the above criteria well and are among the most suitable materials for dating using this method. When they are deposited they contain uranium coprecipitated with the carbonate from the groundwater, but no thorium. Massive speleothem is normally effectively impermeable to groundwater and this prevents leaching of uranium, ensuring that the system remains closed. However in practice many speleothems do not fully satisfy these criteria for the following reasons.

(i) Porous speleothems are liable to leaching and uranium migration and should be avoided wherever possible. Problems are also caused by recrystallised speleothems, which are likely to have gained (or more likely lost)
some uranium in the process. Both porous and recrystallised speleothems thus violate the closed system requirement. Porous speleothems are usually obvious and can be avoided: recrystallised speleothems are sometimes distinguishable from their crystalline texture (often saccharoidal) or can be detected from anomalous isotope ratios (for instance a $^{230}\text{Th}/^{234}\text{U}$ ratio of >1 suggests the sample has lost uranium).

(ii) Dirty speleothems, which contain some insoluble detrital material, violate the requirement that the sample should initially have contained no $^{230}\text{Th}$, since this isotope will be present in the detritus. Detrital contamination is easily detected by measuring activity due to the abundant and long lived isotope $^{232}\text{Th}$, which is also present in the detritus, but absent from clean calcite.

In practice it is impossible to correct for open system behaviour (uranium loss or uptake) in speleothem because there is no way of knowing the original uranium content; thus samples which are likely to have been leached should be discarded. Detrital contamination is a particularly severe problem in dating speleothems associated with clastic sediment bodies since they are likely to be contaminated with the sediment. If not too great, detrital contamination can be corrected for using $^{232}\text{Th}$ as a tracer of the degree of contamination. Various schemes to correct for detrital contamination have been
devised (Schwarcz 1980, 1989, Ku and Liang 1984). These can be roughly subdivided into simple routines that use the activity of $^{232}$Th in a single sample to obtain a rough estimate of the degree of detrital contamination, and the isochron techniques which provide a better estimate of contamination (and hence true age) but require multiple analyses. Detrital contamination correction methods are essential tools in attempting to date Pleistocene sediments, but all correction schemes rely on untestable assumptions and are inherently unreliable: a premium should always be placed upon collecting the cleanest possible samples.

This research used standard alpha-spectrometric U-series dating techniques, described in detail by Gascoyne (1977) and Gascoyne et al. (1978). The method involves dissolution of the speleothem sample and addition of a spike containing artificial isotopes of U and Th. The U and Th are then chemically separated and electrodeposited onto planchettes. The alpha decay activity for each isotope is then measured using an alpha spectrometer. By using the artificial spike, losses during separation can be calculated and the $^{230}$Th/$^{234}$U and $^{234}$U/$^{238}$U activity ratios, and thus the age of the sample, found. Errors are calculated from the counting statistics using the poisson distribution, and are quoted to 1 standard deviation. It should be emphasised that these only comprise counting errors and include no component for other sources of error (such as leaching or other problems).
The spike used (no. 2) was calibrated by J.N. Andrews (Bath University) and P. Rowe (UEA), with conflicting results. Therefore multiple calibration analyses were carried out by D. Richards and the author, against the well-calibrated USIP spike, and against natural uraninite supplied by M. Ivanovitch (which should be in secular equilibrium, with $^{234}\text{U}/^{238}\text{U}$ and $^{230}\text{Th}/^{234}\text{U}$ ratios of 1). A calibration close to that obtained by P. Rowe was obtained. Since the latter had also carried out multiple calibration analyses, and obtained consistent results, the new value was adopted. Previous to this recalibration, work at Bristol had used the Bath calibration for analyses using the no. 2 spike. It was therefore necessary to recalculate ages obtained from these analyses. This affects a number of analyses quoted in this thesis which were carried out by P. L. Smart before the author started work. Analyses from Kent's Cavern, Minchin Hole and Saddle Head Cave (see Minchin Hole) were recalculated, and are noted in the site accounts.

During this research, collection of the cleanest possible samples was attempted, both to minimise problems of detrital contamination, and because dirty speleothems were often found to be porous and thus susceptible to leaching. In addition, detritally contaminated samples were found to be analytically more difficult, often producing low thorium yields. However, a number of dated samples were significantly contaminated with detritus,
revealed by low $^{230}\text{Th}/^{232}\text{Th}$ ratios. A ratio of <20 was taken to indicate the need for correction for detrital contamination. This was carried out using method 1 (equation 8) of Schwarcz (1980). This provides a rough estimate of the degree of detrital contamination and the effect on the calculated age. In most cases the effect on the age was not great (usually under one standard deviation). Thus isochron methods, which are costly and time consuming, were not used.

2.1.3. Electron spin resonance dating.

Electron spin resonance dating is a radiogenic method that can be applied to a variety of crystalline materials including speleothem, corals, molluscs, tooth enamel and quartz (Hennig and Grun 1983, Grun 1989). The method measures the charge population in traps in the crystal lattice, which is proportional to the radiation dose received by the sample. Determination of the annual dose rate then allows the age of the sample to be calculated. ESR dating effectively measures the same signal as used in thermoluminescence dating, but using a different method. ESR dating has the advantage that the measurement is non-destructive so that measurements can be repeated on the same sample.

The upper age limit of ESR dating is defined by:
(a) Saturation: after a large dose the sample becomes saturated and the ESR signal asymptotically approaches an upper limit.

(b) Stability of the ESR signal, which decays slowly with time.

(c) Durability of the sample: recrystallisation will reset the signal resulting in a spuriously low age.

ESR dating of speleothem calcite is described in detail by Smith et al. (1985, 1986), Grun (1989) and Smart et al. (1989). At the time of formation the calcite crystal lattice has no trapped charge (spin) and the ESR signal is zero. With time radiation causes the growth of trapped charge resulting in an increase in the ESR signal. This is measured by ESR spectrometry. An ESR spectrum typically shows several peaks. The peak at $g=2.0005$ has been shown to be the most reliable for dating of speleothem (Smith et al. 1986). This signal has a mean life of around $6 \times 10^7$ years and grows approximately linearly with dose to at least 100 Gray, permitting the dating of old samples. In practice the upper age limit of ESR dating of speleothem calcite is usually set by recrystallisation of the calcite, which has occurred in the majority of samples older than around 500 ka (Smith et al. 1986).
The basic methodology for dating using this signal is given by Smith et al. (1986); their methods were followed in this research. In measuring this signal it is important to avoid interference from other nearby signals. Two interfering signals produced in sample preparation have caused problems in the past. These are the crushing signal at \( g = 2.0001 \), induced by sample grinding, and a short-lived signal at \( g = 2.002 \) produced by artificial irradiation. However they are removed by acid etching and heating (or storage for several months) respectively. The accumulated dose received by the sample is found by the additive dose method. Several aliquots of the sample are measured to find the amplitude of the natural ESR signal. Further aliquots are then irradiated with a range of gamma radiation doses to measure the growth of the ESR signal with increasing radiation dose (fig. 2.3). The natural radiation dose can then be calculated using linear (Smith et al. 1986) or exponential (Grun and Macdonald 1989) curve fitting methods. Linear methods were used in this research since exponential curve fitting requires large artificial radiation exposures in order to work well. Previous work on ESR dating of speleothem has produced good results using linear fit methods (Smith et al. 1986, Smart et al. 1989) and no problems were encountered in the present work.

The environmental dose rate consists of two components which are measured separately. Gamma radiation from the surrounding sediment contributes an external dose. Alpha
Figure 2.3.

Graph showing the additive dose method of determining the accumulated dose (the total natural radiation dose received by a sample since its formation). Aliquots of the sample are irradiated with additional laboratory gamma doses to obtain a growth curve of ESR signal intensity against gamma dose. The accumulated dose can then be determined by extrapolating the growth curve back to zero signal. (After Smith et al. 1986).
and beta radiation from uranium series decay within the speleothem contributes an internal dose. The internal dose is estimated by using uranium series analysis to find the uranium and thorium content of the sample. Measurement of the external dose can be carried out by TL dosimetry or using gamma spectrometry. This is more difficult since gamma radiation has a range of around 50 cm in sediment and it is necessary to site the dosimeter or gamma spectrometer probe in a hole around this deep in order to get a reasonably accurate reading. This in turn introduces problems since it is rarely possible to carry out dosimetry at the exact site from which the sample was taken. Ideally the sample would be taken from a position adjacent to the dosimeter, but in many cases this is impossible and the best that can be achieved is to try to site the dosimeter in a position equivalent to that from which the sample came. For example, if the sample comes from the base of a flowstone floor, the dosimeter would be placed in a similar position adjacent to the base of the floor. In such circumstances it is desirable to place several dosimeters to try to assess any variations in dose rate. TL dosimetry was used, employing copper sheathed CaSO₄: Dy dosimeters. These were inserted into holes as described above. In a few cases holes could not be drilled to the full depth due to boulder obstructions, etc. In such cases spoil was heaped against the sediment face to make up the required depth. TL measurement of the dosimeters was carried out at the British Museum TL laboratory, with the help of N. Debenham.
Once the accumulated dose and the internal and external dose rates are known, the age of the sample can be calculated. In principle this is a simple matter: the age being found by dividing the total accumulated dose by the annual dose. In practice the variation in quantity of uranium series daughters with time means that the internal dose rate will have increased over time, and an iterative approach is used to calculate the age of the sample. Errors are calculated by combining all the errors in the ED and external and internal doses, and are quoted to one standard deviation.

Whilst the ESR signal in the sample may be measured to high precision, estimation of the annual dose is more difficult; in addition to the difficulties outlined above it is likely to have changed with time, for instance due to a change in the water content of sediments. For this reason ESR dating is generally less reliable than uranium-thorium dating of clean speleothem. However, it has two major advantages: it can be applied to dirty samples and has the potential for dating back to an age of around 750 ka.
2.2. The application of dating methods.

2.2.1. General considerations.

In order to use these dating methods to find the age of specific Pleistocene stratigraphic marker horizons in caves, it is necessary to establish several things. First, the nature of the sediments and the feature to be dated must be characterised. Second, the stratigraphic relationships between the sediments of interest and dateable speleothem must be established. These steps are an integral part of the dating process: without this background work any ages obtained are likely to be meaningless.

Many sites of interest were excavated some time ago and descriptions of the sedimentary sequence already exist. Nonetheless it is still generally necessary to examine the sediments (or to collaborate with a worker who has the necessary skills to do so). In the last century geological methods were in their infancy and in particular sedimentary processes in caves were very poorly understood. An extreme example of this is the identification of cave sediments as 'Diluvium', deposited by Noah's flood, by some early workers such as Widger at Torbryan (Walker and Sutcliffe 1967). When dealing with sites of this antiquity it is always necessary to examine the remaining sediments and independently interpret the stratigraphy. The same may apply to much more recently
excavated sites though perhaps for different reasons: some early to mid 20th century excavators appear to have been motivated mainly by the desire to obtain specimens, and paid scant regard to the sedimentary sequence. In contrast to these well known previously excavated sites, others such as the Berry Head caves (this thesis) have never been examined before, but their location and morphology have indicated the possibility of obtaining interesting results. Thus at all sites the stratigraphy and its interpretation needs to be investigated in some detail. Similarly in cases where particular mammal faunas or human industries are the object of interest it is wise to check their interpretation. These are highly specialist fields and the identification of such material is best left to a suitable expert.

2.2.2. Cave sediments.

Cave sediments and their deposition have been reviewed by Rosenfeld (1964b), Sutcliffe (1970), Ford (1975), Laville (1976), and Collcutt (1979, 1985). Collcutt (1985) in particular provides an exhaustive review both of cave sediments and of the wider sedimentological literature.

Although sedimentological processes in caves are generally the same as those that operate on the surface, the analysis of cave sediments is complicated by several problems which are less common or absent in open sites.
Some of these, such as bioturbation, are familiar in open sites but are more often encountered in caves: their frequent use as carnivore dens may lead to a very high degree of disturbance by burrowing animals. A difficulty that is peculiar to caves is the stratigraphic problems that may arise if the cave has experienced several phases of fill. In an open site an orderly stratigraphy exists with the oldest sediments at the base. In caves, by contrast, if an ancient sediment body is eroded, remnants of the sediment may remain adhering to the walls or roof, or bridging voids, as well as on the floor (see the Torbryan Caves, this thesis). Younger sediments may be deposited beneath, and the situation may be further complicated if collapse of ancient sediment occurs during deposition of the younger deposits. Thus an extremely complex stratigraphy may result, in which young sediments may apparently be overlain by much older sediments. Speleothems, in particular, are liable to survive erosion to form wall remnants, often accompanied by the cemented remains of the sediments which lay beneath them. Comparable problems may result from compaction, which can open up a void within a sediment body if the upper part has become cemented and remains supported by the cave walls.

Standard geological mapping techniques have been found to be efficient in characterising cave sediments, and were used for the work described in this thesis. They provide the best method for detecting and untangling the complex
stratigraphy associated with multiple fills (Collcutt 1979, 1985). By inspection and small scale excavation of in-situ sediments, it is possible to get a good idea of the extent and structure of sediment bodies. Sedimentary structures, such as bedding, clast/matrix support of clasts, slump structures etc, can only be described and measured in field sections. A qualitative assessment of compaction, particle size distribution, clast lithology, and clast orientation can also be made in the field.

Field sampling and laboratory analytical methods were used to supplement field mapping at some sites. They are chiefly useful in obtaining quantitative data on specific variables such as clast orientation and particle size distribution. Standard methods were used for laboratory analysis (Avery and Bascomb 1974, Allen et al., 1974) and are noted in the site accounts. In some cases these methods provide valuable information which is otherwise unobtainable (for instance elemental abundances). However it is perhaps doubtful whether the more precise results yielded by laboratory analysis of particle size distribution, for instance, are always worth the considerable time and expense involved. In many cases high precision is just not needed and the analysis essentially generates unnecessary data. This data may in itself be compromised. For instance the small samples which it was necessary to take at Kent’s Cavern were inadequate for accurate characterisation of the coarse sediments (Gale and Hoare 1992) and it is debatable
whether the results are worth the effort of analysis. These considerations suggest that it is not generally worth routine laboratory analysis of all sediments: however, where a specific question needs to be answered there is no doubt that laboratory analysis can be of very great value.

2.2.3. Dating cave sequences.

In order to date the horizon of interest it is necessary to select speleothems suitable for dating and establish their stratigraphic relationships to it. Unlike other methods such as \(^{14}C\) dating of bone and charcoal, or TL dating of flint, it is rarely possible to directly date the horizon of interest using speleothem dating methods. Criteria for selecting samples are given by Schwarcz (1980). Possible situations are shown in fig. 2.4. The closest approximation to a situation where a direct date can be obtained is where the material of interest (for instance bone) is embedded in the speleothem. Even here it is necessary to try to ascertain whether the remains could have been reworked from an older deposit or have sat on the cave floor for some time before deposition.

A more typical situation is where the material of interest is embedded in clastic sediment and it is necessary to locate associated speleothems which are older or younger than the deposit in question. In order
Figure 2.4.

Some possible relationships between speleothems and sediments in caves.

(a) The speleothem encloses and therefore postdates bones and artefacts.

(b) Speleothem floors are interbedded with sediment layers: the lower floor predates layer (1), and the upper floor postdates it.

(c) The broken speleothem block predates the sediment enclosing and overlying it (1), but does not necessarily predate the sediment beneath it (2).

(d) The wall speleothem with associated floor postdates the lower sediment layer (1) but predates the upper layer (2), which buries it.

(e) An ancient wall remnant of a speleothem floor with associated sediment (1), predating the present sediment sequence below (2).
to satisfactorily date the deposit it is necessary to date speleothems in both situations to provide maximum and minimum ages for the deposit. The ideal situation is where the deposit occurs interbedded between speleothem floors. Where blocks of ancient speleothem occur within the deposit they can be used to provide a maximum age. Caution is needed in such cases. Blocks of ancient sediment in the deposit only demonstrably predate the sediment enclosing and overlying it, but not that beneath it. However sometimes it can be argued on stratigraphic grounds that such speleothems may predate the entire sequence, as in Rhinoceros Hole (this thesis). Similarly wall remnants buried by the sediment can provide a maximum age, as can remnants above the deposit if it can be shown that they grew on an older fill which was removed before the deposition of the present sediment.

Given the constraints of selecting samples which can be related to the feature of interest, material suitable for the dating technique being considered should be diligently sought. Uranium series dating requires clean, massive speleothem to obtain good results: ESR dating can cope with dirtier samples but the requirements of environmental dosimetry introduce a different set of constraints. Where the only material directly in contact with a deposit of interest is likely to yield poor results it may be wise to supplement it with better material which may be less easy to relate to the deposit but may be more likely to yield a usable age. It is in
cases such as this that a good appreciation of the site stratigraphy is invaluable, allowing the use of samples of a far higher quality than would be possible were dating restricted to material obviously in contact with the deposit of interest. While schemes for detrital contamination correction exist for U-series dating, and the environmental dose rate may be approximately ascertained from small sediment remnants for ESR dating, such techniques are not reliable and it is far better to seek a more suitable sample in the first place.

In some cases it is only possible to obtain a broad idea of the age range of the deposit, or just a maximum or minimum age. While this situation is obviously not ideal, it is still worth dating the material; the value of a reliable minimum or maximum age for a fauna or other deposit of interest may be considerable, especially if other evidence can be used to further constrain the possible age range.

2.2.4. **Summary.**

In order for useful work to be carried out several criteria must be satisfied:

(a) Deposits must occur which contain evidence of a dateable and widely recognisable chronological marker,
such as a distinctive mammal fauna or marine transgressive sediments.

(b) Dateable speleothem must occur associated with the sediments. If U-series dating is intended, speleothem must be crystalline and massive to ensure that it has remained a closed system, and the detrital content should ideally be low to minimise problems of contamination. It is the requirement for clean speleothem that restricts the choice of sites to caves. Even within caves, many speleothems do not satisfy these criteria, and sampling sites must be selected accordingly. ESR dating can be used to overcome some of these problems, but it is intrinsically less reliable than U-series dating, and it introduces a different set of problems, principally the need to find a site where environmental dosimetry can be carried out.

(c) The stratigraphic relationship between the sediments and dated speleothem must be known. Where this has not been established by previous work (for instance archaeological excavation) it is necessary to undertake mapping and possibly sedimentary analysis to determine the stratigraphy.

Where these criteria are satisfied, the deposit of interest can be dated. Normally speleothem which is stratigraphically higher or lower than the deposit is dated to provide a minimum or maximum age: ideally both
minimum and maximum ages are obtained, either by dating speleothem or in some cases by using biostratigraphic or similar marker horizons.
3. THE BERRY HEAD CAVES.

3.1. Introduction.

Marine erosion platforms and the raised beach deposits which lie upon them have previously provided the major evidence of Pleistocene transgressions in Britain (Zeuner 1959, Mitchell 1977). Such features provide information about the altitude reached by the transgressions which formed them (Mitchell 1977), but their usefulness is limited by the difficulty of dating them. Relative dating by amino acid geochronology has gone some way to solve these problems (Davies 1983, Bowen et al. 1986b), but it is clear that in many cases older beach deposits have been destroyed or reworked by more recent transgressions (Bowen et al. 1986b), and the platforms could considerably predate the sediments upon them.

A complementary source of evidence is provided by coastal karst caves, which frequently contain calcite speleothems, dateable by uranium series analysis. This approach has been used in the tropical carbonate bank setting of the Bahamas, where dating of subaerially formed speleothem in the submarine Blue Holes has been quite successful in delimiting the marine regressions of the Upper Pleistocene (Li et al. 1989, Richards et al. 1994). Dated speleothem has also been used to help to constrain the age of phreatic caves formed during marine transgressions in the same area (Mylroie & Carew 1988).
Little work has as yet been carried out in the coastal limestone regions of Northwest Europe, where in contrast to the Bahamas, large volumes of clastic sediment may be deposited in caves by marine transgressions, which can be dated where they occur interstratified with speleothems that grew in regressive phases. This chapter describes a dated record of marine transgressive caves and cave sediments on Berry Head in Southwest England, which provides the first clear evidence for the elevation reached by transgressions during oxygen isotope stages 5e and 7.

Berry Head lies at the southern end of Torbay in South Devon, (fig. 3.1) and forms one of two Devonian limestone promontories defining the limits of the bay, which has been eroded into softer Devonian slates and Permian conglomerates. The headland is composed of poorly bedded crinoidal limestones and massive reef limestones (the Brixham Limestone), and has been extensively folded and faulted by Hercynian tectonism (Smythe 1973). The limestones are cut by numerous Permo-Triassic sandstone dykes and associated calcite veins infilling later north-south and west-southwest-east-northeast trending tension gashes (Richter 1966).

The morphology of Berry Head is dominated by two very extensive marine erosion platforms. One of these platforms forms the top of the headland at an altitude of around 57 m O.D., and can be traced as a 1 to 2 km wide...
**THE CAVES OF BERRY HEAD**

Map of Berry Head, showing locations of marine erosion platforms and caves. (A) Sweetwater Pot, (B) Corner Cave, (C) Corbridge Resurgence Cave, (D) Rift Cave, (E) Holes in the Wall, (F) The Cavern, (G) Corbridge Cave, (H) Shaky Caves, (I) Berry Head Cave, (J) Hogberry Cave, (K) Starfish Cave, (L) Cuttlefish Cave, (M) Garfish Cave, (N) Corbridge Resurgence.
bench for 5 km to the west along the south side of Torbay. A submerged cliff off the end of Berry Head backs the second platform, which is similar in scale and lies at around -40 m O.D. (Donovan & Stride 1975). The size of these features suggests that the platforms, and Berry Head, must predate the Pleistocene ice ages, since they are too large to have been formed during the relatively brief sea level still-stands of this period. Donovan and Stride (1975) suggest a Tertiary age for the -40 m platform, citing the Tertiary freshwater limestones found in the English Channel by Curry et al. (1971) as evidence that sea levels fell low enough during the Tertiary for it to have been formed at that time.

A series of four much smaller marine erosion platforms is preserved on the flanks of Berry Head (fig. 3.1). The lowest of these platforms, with a seaward edge at approximately -15 m O.D., forms a submerged bench some 50 m wide off the end of the headland, and can be identified on Admiralty charts as a wide feature extending several km to the south; it is also preserved off Hope's Nose to the north. Two narrow platforms just above present sea level, with seaward edges at around 3 m O.D. (range 2 to 5 m O.D.) and 8.5 m O.D. (range 6 to 9 m O.D.) are well known at several limestone outcrops around Torbay, and are well preserved around Berry Head. Raised beach deposits occur on the 8.5 m platform at Hope's Nose and Thatcher Rock on the north side of Torbay, and in the south at Shoalstone on the north side of Berry Head (fig.
3.1). They have been described by Mottershead et al. (1987) and three broad facies were recognized. At Hope's Nose gritty sands with shells were interpreted as sediments deposited in an intertidal or subtidal environment. Overlying these sediments and separated from them by a reddened layer possibly representing a period of weathering are dune sands containing marine molluscs. At Thatcher Rock and Shoalstone a simpler stratigraphy is present with cobble deposits interpreted as storm beaches deposited around or above the contemporary high water mark.

The age of the beaches has been investigated using aminostratigraphy (Davies 1985, Bowen et al. 1986b). Davies (1985) considered the Thatcher Rock and Shoalstone beaches to belong to her aminogroup 3, dated to a transgression at around 125 ka. during oxygen isotope stage 5e. The Hope's Nose gritty sands gave higher D/L ratios suggesting that they should be correlated with her aminogroup 4, tentatively dated by racemisation reaction kinetics to 200±20 ka. (oxygen isotope stage 7). Bowen et al. (1986b) presented rather more analyses and suggested a different interpretation. They correlated the Hope's Nose gritty sands with their Minchin Stage (Davies aminogroup 4, isotope stage 7?) and the overlying dune sands with their Pennard Stage (Davies aminogroup 3, isotope stage 5e). However, they considered that the Shoalstone and Thatcher Rock beaches produced D/L ratios too high to be correlated with the Pennard Stage and suggested that
these belonged to a third aminogroup, the Unnamed Stage, possibly representing beaches intermediate in age between the Pennard Stage and Minchin Stage beaches. Campbell and Bowen (1989) suggested that both the Minchin Stage and the Unnamed Stage date from isotope stage 7 implying that the Shoalstone and Thatcher Rock beaches date from that time, conflicting with Davies' conclusion that they date from isotope stage 5e. The effects of temperature differences between sites were ignored by Bowen et al. (1986b) and Campbell and Bowen (1989). However, this approach is disputed by Hollin et al. (1993), who found significant differences between the majority of open sites and the caves, such as Minchin Hole (this thesis), where the aminostratigraphy was calibrated by dating associated speleothems. Hollin et al. (1993) suggest that the Unnamed Stage of open sites correlates with the Pennard Stage in the caves, and dates from isotope stage 5e, and that the Pennard Stage of open sites dates from a transgression late in isotope stage 5.

Above the 8.5 m platform the sea cliffs are considerably degraded and any higher platforms are mostly destroyed or mantled by scree; however a prominent horizontal ledge cutting across the geological structure at 28 m O.D. on the east side of Oxley Head (fig. 3.1) has been tentatively identified as a fourth minor marine erosion platform, although the surveying necessary to identify this platform elsewhere around Torbay has not been carried out. The small scale and good preservation of
these minor marine erosion platforms, and the association of the 8.5 m platform with extensive Pleistocene raised beach deposits, suggests that they formed during short lived transgressive sea level still-stands during the Middle and Upper Pleistocene, in contrast to the major platforms which are almost certainly much older.

3.2. The Berry Head Caves.

The coastal situation of the Berry Head limestone must have significantly influenced its karstic evolution and cave development on the headland. Berry Head has been in a coastal situation (at least at times of high sea level) for much of the Pleistocene and probably longer, and it is surrounded on three sides by the sea: the position of the groundwater table will have been directly determined by sea level.

The north side of the headland has been extensively quarried, exposing numerous caves (fig. 3.1), the geomorphology of which are discussed in detail in Proctor (1988). They show characteristic features, including irregular passage networks and solution pockets on the walls and roof, that show that they formed by solution in a phreatic (sub water table) environment. The quarry caves occur over an altitude range of -15 m O.D. to 29 m O.D. (fig. 3.2). The passages fall clearly into two morphological types: (1) vertical and steeply sloping
Figure 3.2. Extended elevation of the Berry Head Caves, showing the occurrence of extensive horizontal passages and large chambers just below the altitudes of marine erosion platforms. (A) Sweetwater Pot, (B) Corner Cave, (C) Corbridge Resurgence Cave, (D) Rift Cave, (E) Holes in the Wall, (F) The Cavern, (G) Corbridge Cave, (H) Shaky Caves, (I) Berry Head Cave, (J) Hogberry Cave, (K) Starfish Cave, (L) Cuttlefish Cave, (M) Garfish Cave.
passages, (2) horizontal passages and chambers, often forming networks. Horizontal passages and networks tend to lie at similar altitudes right across the headland; a plot of plan area of cave passage against altitude for all the caves studied (fig. 3.3) shows that although cave development occurs over an altitude range of 44 m, major horizontal cave development is restricted to three distinct levels: -2 to 2 m O.D., 5 to 9 m O.D., and 22 to 26 m O.D. These horizontal passages cut across the dipping geological structures, and the presence of horizontal cave development at the same levels across the headland must be due to a hydrological control on cave formation, such as the position of the water table.

Comparison of the levels of major horizontal cave development with the altitudes of marine erosion platforms shows that the horizontal caves occur between 2 and 6 m below the altitudes of the platforms on the flanks of the headland (fig. 3.3). This position several metres below each marine erosion platform (which marks approximate sea level and hence the altitude of the water table) implies that they probably formed not at the water table but at the halocline beneath a shallow freshwater lens a few metres thick and underlain by saline groundwater (Palmer and Williams 1984, Back et al. 1986). This is confirmed by the morphology of the Berry Head caves, which show many features characteristic of halocline caves in the Bahamas such as mazes, isolated chambers and passages terminating in blank walls (Palmer
Figure 3.3.

Graph of altitude against the total explored area of cave development in the Berry Head Quarry Caves, showing the relationship between the altitudes of marine erosion platforms and the total area of cave development.
et al. 1986, Vogel et al. 1990). In particular, the morphology of the low, wide chambers in Corbridge Cave (fig. 3.4) is strikingly similar to that of chambers in halocline caves such as Lighthouse Cave, San Salvador, with floors of collapsed slabs sloping down into lower level passages around the chamber margins (Mylroie and Carew 1988). The close association between the horizontal cave systems and marine erosion platforms suggests that major transgressive sea level still-stands reached altitudes of around 3 m O.D., 8.5 m O.D. and 29 m O.D. in the Middle and Upper Pleistocene. The extensive horizontal cave systems between 22 and 26 m O.D. on Berry Head provide much more convincing evidence of a sea level still-stand at 29 m O.D. than the degraded Oxley Head platform. In addition the absence of major horizontal cave systems outside these altitude ranges implies that there have been no long lived sea level still-stands at other altitudes in the period of cave formation (probably the Middle and Upper Pleistocene).

3.3. The Cave Sediments.

The caves contain extensive sediment deposits. Low-level cave development at altitudes of 5-9 m O.D. is concentrated almost entirely in Corbridge Cave. The latter comprises a series of wide low chambers at an altitude of between 5 and 10 m O.D. (fig. 3.4). The north and west sides of the chambers slope down into an active
Figure 3.4. Plan of sediments and speleothem sampling sites in Corbridge Cave.
tidal creek connecting a pool in Berry Head Quarry with the sea (figs. 3.1, 3.4), and a series of steep ramping passages connects the system with high-level caves above. The passages and chambers of the cave are floored by extensive sediment deposits. Sediments at altitudes of over 20 m O.D. occur in numerous small caves across the headland. These caves tend to form isolated rifts and small chambers, but similar sequences can be seen in Corner Cave, the Hole in the Wall no.1, the Cavern, Berry Head Cave and Hogberry Cave.

The deposits were mapped (figs. 3.4, 3.5, 3.6) and sediment samples taken: their particle size distribution was examined by sieving using standard methods (Avery and Bascomb 1974), and the lithology of the gravel (>2mm) fraction examined using a binocular microscope. The particle size distribution is given in table 3.1. The following units are recognised.

(a) **Grey Laminated Muds**: comprising greyish brown clayey silts with some fine sand (table 3.1), forming banks along the edges of the tidal creeks in the lowest levels of Corbridge Cave (fig. 3.4). These mudbanks have a distinctive morphology: they are topped by a flat terrace at 2 to 2.2 m O.D. (about the high water mark of spring tides in the cave), and have steeply sloping sides extending to below low water mark in the creeks, which form a trench between the mudbanks and the wall (fig. 3.4). Where the Grey Laminated Muds contain a small
<table>
<thead>
<tr>
<th>Unit</th>
<th>Sample</th>
<th>Site</th>
<th>Mud</th>
<th>Fine sand (63-250µm)</th>
<th>Coarse sand (250-625µm)</th>
<th>Gravel (&gt;2mm)</th>
<th>Foraminifera</th>
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<td>Grey</td>
<td>CC8</td>
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<td>QC2</td>
<td>Rift Cave</td>
<td>70.16</td>
<td>11.78</td>
<td>9.77</td>
<td>6.26</td>
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<td></td>
<td>QC7</td>
<td>Corner Cave</td>
<td>58.09</td>
<td>20.25</td>
<td>20.56</td>
<td>1.11</td>
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</tr>
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<td></td>
<td>QC17</td>
<td>Cavern</td>
<td>72.83</td>
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<td>7.25</td>
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<td>CC19/R</td>
<td>Corbridge Cave</td>
<td>54.51</td>
<td>27.93</td>
<td>15.98</td>
<td>1.60</td>
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<td>46.95</td>
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<td>Absent</td>
</tr>
<tr>
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<td>Corner Cave</td>
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</tr>
<tr>
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<td>QC5</td>
<td>Corner Cave</td>
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<td>0.56</td>
<td>0.24</td>
<td>0.20</td>
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<td>Breccia (Bulk)</td>
<td>QC11</td>
<td>Hogberry Cave</td>
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<td>0.96</td>
<td>0.85</td>
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<td>Hogberry Cave</td>
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<td>1.55</td>
<td>3.71</td>
<td>1.07</td>
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<td>QC14B</td>
<td>Hogberry Cave</td>
<td>80.22</td>
<td>6.97</td>
<td>2.99</td>
<td>9.82</td>
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<td>Cavern</td>
<td>92.39</td>
<td>4.39</td>
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<td>HIW no. 1</td>
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<td>QC5LF</td>
<td>Corner Cave</td>
<td>98.85</td>
<td>1.14</td>
<td>0.01</td>
<td>0.00</td>
<td>Absent</td>
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<tr>
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<td>QC12LF</td>
<td>Hogberry Cave</td>
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<td>HIW no. 1</td>
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<td>0.68</td>
<td>0.29</td>
<td>0.00</td>
<td>Absent</td>
</tr>
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* contaminated with fragments of speleothem floor (QC13) enclosing sediment fragments.

**TABLE 3.1.**

Particle size analyses from the Berry head Caves (weight %).
quantity of sand, they can be seen to be laminated; elsewhere they are thixotropic and this feature cannot be seen.

(b) **Brown Laminated Muds**: clayey silts, with a similar particle size distribution to the Grey Laminated Muds, (one sample contains some gravel, which consists of limestone and speleothem fragments derived from the cave walls or roof) (table 3.1). The Brown Laminated Muds form extensive banks in Corbridge Cave which are similar in morphology to the Grey Laminated Muds unit; they have a flat terrace top at around 5.8 m O.D. and the sides of the banks slope down into a trench feature on the north and west sides of the cave (figs. 3.4, 3.5.). The surface 15 to 20 cm comprises heavily bioturbated mud pellets, but below this level the sediment is laminated: the laminae generally parallel the surface slope of the mudbanks. Where the contact between the Brown Laminated Muds and the Grey Laminated Muds is preserved, the latter overlie the Brown Laminated Muds.

(c) **Muddy Breccia**: a heterogeneous jumbled mixture of clayey silts, sand and gravel with fragments of limestone and speleothem, and limestone boulders. It contains significantly more medium to coarse sand and gravel than the laminated sediments (table 3.1); the gravel fraction in the sample examined was found to comprise speleothem and carbonate concretions. The Muddy Breccia forms a low bank on the south side of the banks of Brown Laminated...
Muds in the eastern part of Corbridge Cave, and extends up to around 7.2 m O.D. (figs. 3.4, 3.5). This unit dips below the Brown Laminated Muds at the contact, although the situation is complicated by thin spreads of Muddy Breccia which have been washed down over the Brown Laminated Muds.

(d) Colluvium: comprising a jumbled mix of silts, clay, sand, fragments of speleothem and limestone, and limestone and sandstone boulders. Like the Muddy Breccia, the sieved samples contain a significant amount of medium to coarse sand and gravel (table 3.1). The gravel fraction shows a diverse lithology, containing limestone, speleothem, carbonate concretions, sandstone, calcite crystals, quartz gravel and limonite. It forms steeply sloping deposits in ramping passages, or mounds below holes in the roof.

(e) Laminate Breccia: a conglomerate of fragments of clayey silts in a chaotic matrix of poorly sorted sediment resembling the Colluvium. The proportion of the chaotic matrix varies; there is very little present in the sediment at some sites. The gravel fraction includes limonite, speleothem, and calcite crystals. The clayey silt fragments are laminated, and show a similar particle size distribution to the Laminated Muds (table 3.1). The Laminate Breccia is present at altitudes of between 22 and 25 m in widely separated caves across the headland including Corner Cave, the Hole in the Wall no.1, the
Cavern, Berry Head Cave and Hogberry Cave, forming small remnant patches on the floor and in wall pockets (fig. 3.6). It is overlain by Colluvium in the Cavern.

(f) **Red Sands**: comprising silty sands, forming thin spreads capping all other units. This unit contains a very high proportion of sand (table 3.1). The gravel fraction comprises speleothem fragments, carbonate concretions, calcite crystals and limonite. The spreads are restricted to areas below exposures of sandstone dykes in the cave walls and roof, and represent material recently weathered from them. For clarity these are not included on the cave plan (fig. 3.4).

The Grey Laminated Mud is a water laid deposit: its distribution as flat topped mud banks bordering an active tidal creek and extending up to the modern high water mark of spring tides strongly suggests that the Grey Laminated Muds are a modern ponding deposit laid down by the tidal creek during high tides. This is confirmed by the deposition of Grey Laminated Muds on items left in the creeks. The Brown Laminated Muds have similar features to the Grey Laminated Muds. The presence of laminations, and the fine grained nature of the sediment suggest that it is a ponding deposit, laid down in calm water conditions (Bull 1977, 1981). The laminae within the sediment banks dip down into the trenches to the north and west, suggesting that this is a fossil tidal creek, and that the Brown Laminated Muds were deposited
by an earlier marine transgression, with a high water mark of spring tides at around 5.8 m O.D.

The Laminate Breccia comprises the remains of fine grained laminated sediment which filled several of the high level caves. The fine grain size and laminae suggest it is a ponding deposit (Bull 1977, 1981). The Laminate Breccia could be attributed to unconnected episodes of freshwater ponding in separate caves due to choking of lower outlet passages with mud. Alternatively it might have been deposited during a regional rise in the water table caused by a marine transgression, which would have synchronously flooded all the caves to the same altitude. The presence of Laminate Breccia in widely separated caves within a narrow altitude range of 22 to 25 m O.D. suggests its deposition was the result of a regional rise in the water table. Thus it probably represents the eroded remnants of another transgressive deposit. The brecciated state of the sediment shows that it has suffered extensive erosion and collapse since its deposition. In Hogberry Cave and the Hole in the Wall no.1 it is associated with hanging speleothem floors which contain fragments of laminated sediment in their bases, and probably record the original height of the sediment which has been eroded out from beneath (fig. 3.6).

The Colluvium is clearly a slope deposit comprising talus and mud washed down from the higher level caves; the
varied lithology of the gravel fraction suggests that some at least of this material is derived from the surface above. The fine material in the Colluvium is probably reworked from soils capping the limestone plateau above (Griffiths and Lee 1989); there are no sediments within the caves which extend high enough to act as a plausible sediment source. On the evidence of morphology and lithology, the origin of the Muddy Breccia is problematic, although it predates the Brown Laminated Muds. Its morphology, comprising low banks not associated with any source passages, suggest it cannot be a slope deposit like the Colluvium. The gravel fraction is also restricted in lithology, supporting this conclusion.

3.4. Origin of the laminated muds.

The lithology and morphology of the sediment bodies suggests that the Grey Laminated Muds are a modern water laid deposit being deposited by the present high sea level, and that the Brown Laminated Muds were deposited by an earlier higher marine transgression. Two approaches were used to test this hypothesis. The sediments were analysed for exchangeable cations to determine if they retained a seawater signature, and microscopic examination was used to search for marine microfossils.

Determination of exchangeable cations was carried out by standard methods (Avery & Bascomb 1974, Allen et al.)
1974), using pH 9 ammonium acetate for extraction, and atomic absorption spectrophotometry for determination of calcium and magnesium, and flame photometry for sodium and potassium. The results are given in table 3.2. Multiple samples from each unit generally gave similar results, except for one sample of Brown Laminated Muds which lay close to the modern high tide mark and contained high quantities of sodium, potassium and magnesium, showing that it has recently been saturated with sea water, probably by capillary rise into the sediment. The Grey Laminated Muds show similar high concentrations of these elements, indicative of the position of the muds below the high tide mark, also resulting in their saturation with sea water. All the other units are similar, with much lower concentrations of sodium, potassium and magnesium, and slightly higher concentrations of calcium. There is no significant difference between the Brown Laminated Muds and the other units, suggesting that if the Brown Laminated Muds were marine deposited, their original high sodium, potassium and magnesium content has long ago been leached by percolating groundwaters and it is not possible to determine their environment of deposition by this means.

Microscopic examination for marine microfossils was carried out on the 0.063 to 0.125 mm and 0.125 to 0.25 mm fractions of the sieve samples (see above) under a binocular microscope. Samples found to contain fossils were passed on to B.M. Funnell for detailed
<table>
<thead>
<tr>
<th>Unit</th>
<th>No. of samples</th>
<th>Ca (mg g⁻¹)</th>
<th>Mg (mg g⁻¹)</th>
<th>Na (mg g⁻¹)</th>
<th>K (mg g⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brown Laminated Muds</td>
<td>10</td>
<td>228±19</td>
<td>190±37</td>
<td>91±21</td>
<td>119±15</td>
</tr>
<tr>
<td>Brown Laminated Muds (Saturated)</td>
<td>1</td>
<td>241</td>
<td>769</td>
<td>4090</td>
<td>634</td>
</tr>
<tr>
<td>Grey Laminated Muds</td>
<td>5</td>
<td>144±23</td>
<td>1000±300</td>
<td>6170±1890</td>
<td>685±145</td>
</tr>
<tr>
<td>Colluvium</td>
<td>5</td>
<td>270±47</td>
<td>250±24</td>
<td>114±7</td>
<td>177±29</td>
</tr>
<tr>
<td>Red Sands</td>
<td>2</td>
<td>280±19</td>
<td>212±19</td>
<td>81±9</td>
<td>114±1</td>
</tr>
<tr>
<td>Muddy Breccia</td>
<td>1</td>
<td>248</td>
<td>198</td>
<td>107</td>
<td>134</td>
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</table>

**TABLE 3.2.**

Chemical analyses from Corbridge cave.
identification. A variety of fossils were found including foraminifera (the most widely distributed), ostracods, sponge spicules, echinoid spines and other echinoderm skeletal elements. The foraminifera present are all species found in the Western English Channel at the present day, implying similar (interglacial) climatic and environmental conditions during their deposition (Funnell 1991). The results are given in table 3.1. All the samples of Grey Laminated Muds and Brown Laminated Muds contain foraminifera, but they are absent from the Laminate Breccia, the Colluvium and the Red Sands. There are two potential sources for the foraminifera: either they are derived from older sediments higher in the cave system, or they are in a primary context and show that the sediment was deposited by a marine transgression. Their absence from the Laminate Breccia and the slope deposits represented by the Colluvium implies that they are not derived from older sediments higher in the caves, since they would then be present in these units. It is therefore concluded that the foraminifera in the Grey Laminated Muds and the Brown Laminated Muds are in primary context, indicating that these sediments have been deposited by marine transgressions. Foraminifera were also found in the Muddy Breccia, although in smaller quantities than in the laminated muds. A possible explanation is that this unit represents the eroded and collapsed remnants of a bank of sediment originally similar to the Brown Laminated Muds. This interpretation is supported by the occurrence of banks of Muddy Breccia.
flanking one side of the Brown Laminated Muds, suggesting that the Muddy Breccia once formed a terrace similar to (but higher than) the Brown Laminated Muds, which was eroded and collapsed possibly during the Brown Laminated Muds transgression. An alternative explanation, that the foraminifera were introduced into the Muddy Breccia during the Brown Laminated Muds transgression can be dismissed, since the Muddy Breccia lies above the limit of this transgression (indicated by the elevation of the top of the Brown Laminated Muds).

The absence of foraminifera from the Laminate Breccia might be taken to imply that it is not a marine transgressive deposit. However their absence is probably for taphonomic reasons. Funnell (1991) has suggested the species present could not have lived in the cave and must have been washed in. All the foraminifera were recovered from sediments in Corbridge Cave, which has a relatively direct connection with the sea via the tidal creek. Progressively older sediments contain less foraminifera, hinting that this connection has enlarged with time. The Laminate Breccia in the high-level caves was deposited in an environment which probably did not have such a direct connection with the open sea; thus foraminifera are absent. The absence of foraminifera notwithstanding, the lithology of the Laminate Breccia, and its occurrence in widely separated caves within a narrow altitude range, suggests it was deposited by a regional rise in the water table that affected the whole headland. The most
reasonable explanation for this remains a marine transgression.

The conclusion that most of the foraminifera in the Corbridge Cave sediments were washed in from the sea outside implies that clastic sediment could have entered the cave by the same route, possibly accounting for much of the volume deposited. This sediment source is much less plausible for the Laminate Breccia, which contains no foraminifera. An alternative source of sediment is indicated by the Colluvium, which is probably derived from the soils capping the limestone plateau (see above). This suggests there was a significant input of sediment washed down into the caves from the ground surface above, which could have been reworked and incorporated into the marine transgressive deposits (Bull 1977, 1981). In the case of the Laminate Breccia, this may have been the major sediment source. It is likely to have declined in importance over time as connections to the sea opened up, but may be significant even today. Spreads of Colluvium extend down to the tidal pools on the west side of Corbridge Cave, and Colluvium must wash down into the pools, providing a source of sediment for the Grey Laminated Muds.

Thus the cave sediments preserve evidence of several interglacial marine transgressions. The Grey Laminated Muds represent sediment deposited by the modern transgression and occur as terraces with a flat top at
the modern high water mark. The Brown Laminated Muds were deposited by an earlier transgression, and occur as a terrace with a flat top at 5.8 m O.D. By analogy with the Grey Laminated Muds this indicates the high water mark at the time of deposition, and a sea level about 3.6 m above the present. The Muddy Breccia represents the eroded remnants of sediments deposited by a third transgression, which predates the Brown Laminated Muds. No terrace top to the Muddy Breccia is preserved, but the high water mark must have been at or above the highest sediments now seen, at around 7.2 m O.D. The Laminate Breccia provides evidence for a fourth transgression reaching to at least 25 m O.D. The age of these marine transgressions is discussed below.

3.5. Age of the marine transgressive sediments.

Uranium series dating of speleothems associated with the sediments was used to obtain estimates of the ages of the marine transgressions inferred from sedimentary analysis. Speleothems from Corbridge Cave, Hole in the Wall no.1 and Hogberry Cave were obtained (figs. 3.4, 3.5, 3.6): the analytical data and ages determined are summarised in table 3.3. Several samples showed $^{230}$Th/$^{232}$Th ratios of less than 20, indicating that significant detrital contamination had occurred. An estimate of the true age was obtained using the correction method 1 (equation 8)
Figure 3.5. Elevations of speleothem sampling sites in Corbridge Cave. Uranium series dates are in ka, and are corrected for detrital contamination.
(a) **Hogberry Cave**
Elevation of rift at entrance

**Figure 3.6.**
Elevations of speleothem sampling sites in Hogberry Cave and Hole in the Wall no.1. Uranium series dates are in ka, and are corrected for detrital contamination.
TABLE 3.3.
Uranium series analyses from the Berry Head Caves.
of Schwarcz (1980). In all but two of the samples this correction was less than 1 standard deviation.

Speleothems from four sites in Corbridge Cave were dated (figs. 3.4, 3.5). At site 1, a layer of Brown Laminated Muds (CC1DBr, table 3.1) is interbedded between two speleothem layers. The lower speleothem (CC1B), which has a redissolved top overlain by the Brown Laminated Muds, yielded two ages of 173 (154-197) and 145 (135-155) ka on a single growth layer near the base, and an age of 210 (188-238) ka on the top layer. The top age is likely to be too old due to leaching since the top of the speleothem is redissolved: the lower ages overlap at one standard deviation and are probably more reliable. These predate the overlying Brown Laminated Muds; in addition this speleothem grew on a sediment floor, now destroyed, showing that sediment deposits existed at that time. The speleothem overlying the Brown Laminated Muds (CC1C) yielded a basal age of 116 (107-125) ka and a middle age of 107 (93-122) ka. Thus the Brown Laminated Muds date from a period between around 155 and 116 ka. The top of the upper flowstone is clean and undissolved, showing that it has not been submerged since its formation.

At site 2, a partially redissolved speleothem flow (CC5), dated to 244 (215-286) ka has remnants of Brown Laminated Muds in solution pockets, and was clearly buried by this deposit, a bank of which is preserved across the passage. Thus it provides a maximum age for the Brown Laminated
Muds as well as a minimum age for this part of the cave.
However it should be noted that only one age estimate was
obtained and that the speleothem was redissolved:
leaching could have occurred and the age may be an
overestimate.

At site 3, a slab of flowstone partly detached from the
wall (CC50) gives a middle age of 226 (150-579) ka and a
top age of greater than infinity. The latter is certainly
erroneous, and can probably be attributed to uranium loss
due to leaching. Nearby, a flowstone floor (CC51) which
grew on a now destroyed sediment floor was dated to 210
(184-244) ka. A bank of Muddy Breccia lies opposite this
floor, suggesting that the speleothem may have grown on a
bank of Muddy Breccia now partly eroded away. Small
sediment remnants adhering to the base of the speleothem
were found to contain foraminifera, suggesting that this
is the case, and that the floor provides a minimum age
for the Muddy Breccia. A speleothem floor resting on the
bank of Muddy Breccia (CC47) yielded an age of 138 (129-
148) ka, consistent with the above conclusion. This floor
had broken up suggesting the Muddy Breccia was eroded
after its deposition.

At site 4, a small speleothem boss (CC28), which grew
over remnants of Brown Laminated Muds, yielded ages of
6.0 (5.3-6.6) ka and 7.9 (7.1-8.6) ka. These give a
minimum age for the Brown Laminated Muds, but provide
considerably less constraint than at site 1.
The dated speleothem interstratified with the Brown Laminated Muds at site 1 shows that this unit was deposited between around 155 ka and 116 ka. The only major transgression known to occur within this period (Li et al. 1989, Gallup et al. 1994), to which the Brown Laminated Muds could be referred, is oxygen isotope stage 5e at between 130 and 122 ka (Edwards et al. 1987). The other sites (2, 3, 4) provide age estimates consistent with this interpretation, though they provide considerably less constraint to the age of the Brown Laminated Muds than at site 1. At two sites (1, 3) speleothem floors grew on sediments which have since been destroyed. The occurrence of foraminifera in sediment remnants on the base of one of these floors (CC51, dated to around 210 ka) and the proximity of this floor to a bank of Muddy Breccia suggests that these floors grew on banks of marine deposited sediment of which the Muddy Breccia represents the degraded remnants. The ages of around 155 and 210 ka obtained for these floors provides a minimum age for this transgression. The older age falls within the 186 to 245 ka age range of oxygen isotope stage 7 (Imbrie et al. 1984, van den Bogaard et al. 1989), and is close in age to the stage 7 transgression reported by Gallup et al. (1994). This suggests a correlation with this interglacial. Further evidence for a transgression during isotope stage 7 is provided by the lack of any speleothem predating stage 7, suggesting that either the
cave was formed then, or a major erosion phase at that time destroyed any earlier speleothem.

Two samples associated with the Laminate Breccia in the high-level caves were dated (fig. 3.6). QC21, a hanging wall remnant of speleothem in the upper chamber of Hole in the Wall no.1, had fragments of laminated sediment in its base. The sediment on which the speleothem grew had been almost completely eroded away but remnant deposits of Laminate Breccia are present on the floor of the chamber and in wall pockets. The speleothem yielded an age of 328 (288-392) ka. The second sample, QC13A from Hogberry Cave, occupied a similar position. This was a massive flowstone floor forming the floor to Hogberry Cave and sectioned by the quarry face at the cave entrance. Beneath the floor a cavity has been produced by erosion of the sediment beneath. Laminate Breccia remnants remain flooring the cavity and in wall pockets, and the speleothem floor was found to contain abundant fragments of laminated sediment cemented into its base. The speleothem yielded an age of 332 (287-412) ka.

At both sites the speleothems contain fragments of laminated sediment, and are associated with nearby deposits of the Laminated Breccia. This strongly suggests that they grew on the surface of the Laminated Breccia (or the original laminated sediment of which it is a remnant). Thus these speleothems give a minimum age for the Laminate Breccia. The two ages agree closely and
suggest an age of around 330 ka or earlier. This is very close to the peak of oxygen isotope stage 9 (at 330 ka, Imbrie et al. 1984) and with the age of the stage 9 regression in the Bahamas (D.A. Richards & P.L. Smart, unpublished data) and it is tempting to conclude that the Laminate Breccia dates from a transgression in isotope stage 9. However an earlier age cannot be discounted: the speleothems may not have grown until some time after the deposition of the sediments. In addition these ages lie close to the upper age limit of uranium series dating. Both have large standard deviations: the possibility that one or both is significantly older cannot be ignored. A stage 11 or even earlier age would be consistent with the uncertainties in the ages obtained.

Combining the information provided by the sediments and the dated speleothem discussed above, there is evidence in the Berry Head caves of three Pleistocene transgressions; a rise to a high water mark of spring tides at 5.8 m O.D. during oxygen isotope stage 5e, an earlier rise to at least 7.2 m O.D., probably during isotope stage 7, and a transgression to at least 25 m O.D. during isotope stage 9 or earlier.

3.6. Discussion.

Comparing the dated record of Pleistocene transgressions obtained from the caves with that provided by raised
beaches in Torbay, the cave transgression record is in agreement with the interpretation placed upon the age of the beaches by Davies (1985), model 1a of Bowen et al. (1986b) and Mottershead et al. (1987). They propose that the intertidal or subtidal gritty sands at Hope's Nose (correlated by Bowen et al. (1986b) with the Minchin Stage) were deposited by a sea level rise to at least 10 m O.D. during oxygen isotope stage 7, and that the later (Bowen et al.'s (1986b) Unnamed and Pennard Stage) beaches were deposited above high water mark during isotope stage 5e; this is fully consistent with the timing and altitude of transgressions inferred from the cave deposits.

Campbell and Bowen's (1989) suggestion that the Unnamed Stage dates from a third transgression intermediate in age between the Minchin and Pennard Stages, and dating from late in isotope stage 7, is more problematical. This would require the Shoalstone and Thatcher Rock beaches to date from that time, implying that these beaches escaped erosion during the isotope stage 5e transgression. Given that at both sites the sediments are only partly cemented (Mottershead et al. 1987) and lie less than 3 m above the stage 5e high water mark, well within the reach of storm waves at that time, this seems highly improbable. The Shoalstone beach outcrops along several hundred m of coastline, yet nowhere is any evidence of later wave erosion seen, nor is there any later beach sediment overlying the Shoalstone beach.
Hollin et al.'s (1993) proposal that the Unnamed Stage dates from oxygen isotope stage 5e is consistent with the work reported here. However, their suggestion that a further, Pennard Stage, transgression occurred later during isotope stage 5 is again subject to the criticism that the Shoalstone and Thatcher Rock beaches show no evidence of erosion or reworking. Furthermore, there is no evidence in the caves of any late stage 5 transgression significantly above the modern sea level. The growth of a speleothem flow (CC1C) at this time at an altitude of around 4.5 m O.D. demonstrates conclusively that there can have been no late stage 5 transgression higher than around 2.5 m above the present sea level, and even a lower transgression would be expected to have reworked the banks of Brown Laminated Muds.

A correlation of the Minchin Stage with isotope stage 7, and the Unnamed and Pennard Stages with isotope stage 5e is preferred here for the reasons outlined above. In addition there is no lithostratigraphic evidence either in the Torbay raised beaches (Mottershead et al. 1987) or in the cave sediments for more than two Pleistocene transgressions within the 5-10 m altitude range, as required by the models of Campbell and Bowen (1989) and Hollin et al. (1993). The high D/L ratios observed in the Unnamed Stage beaches may perhaps be attributable to their deposition early in isotope stage 5e, in contrast to the Pennard Stage which might represent later beaches left behind by the regression at the end of stage 5e.
Alternatively the differences between the Unnamed and Pennard Stage beaches might merely reflect differences in their temperature history, due for instance to differences in burial depth. Further evidence would be required to test either hypothesis.

The results of this study confirm the applicability of coastal karst studies to problems of Pleistocene sea level variations in temperate areas. The cave record provides considerable advantages to neighbouring open sites. The horizontal passage systems provide a record analogous to the marine erosion platforms, but much less vulnerable to destruction and thus more complete. The marine deposited sediments in the Berry Head caves provide the opportunity to directly date marine transgressions, as well as providing a longer record and more precise estimates of the altitude reached by transgressions than the raised beaches. However the cave sediments highlight a problem that also occurs with raised beach deposits: the destruction of early transgressive sediments by later transgressions to a similar altitude. The oldest sediments, the Laminate Breccia and the Muddy Breccia are worst affected and this erosion of early deposits imposes a practical limit on how long the record can be extended back in time. In addition the formation of the cave passages themselves cannot be easily dated, since the speleothem deposits are necessarily younger than the cave. In Corbridge Cave the presence of phreatic passages connecting the cave with
high level chambers at an altitude of 28 m O.D. implies that at least part of the cave must have been in existence when these high level caves were forming, considerably earlier than the earliest dated speleothems in Corbridge Cave itself. Thus while the altitudinal distribution of cave passages provides a complementary record of Pleistocene high sea level still stands to the marine erosion platforms, they do not solve all the problems of dating, for similar reasons; dateable sediments, whether overlying platforms or in caves, could considerably postdate the features with which they are associated.
4. KENT'S CAVERN.

4.1. Introduction.

Kent's Cavern occupies an important position in the British Pleistocene for two reasons. Firstly the cave is of historical significance as one of the sites at which evidence of the antiquity of man was first demonstrated. It was thus instrumental in the scientific revolution of the last century, which freed the geological and biological sciences from the need to conform with the biblical notion of a world created by God a few thousand years previously. Secondly it is a major Palaeolithic site in its own right, having a long Devensian sequence with copious evidence of human occupation, and a much earlier Middle Pleistocene deposit also with a Palaeolithic industry (Campbell and Sampson 1971).

Kent's Cavern is situated in Wellswood, 2 km east of Torquay town centre, in the southern end of an outcrop of Middle Devonian Walls Hill Limestone stretching 2 km to the northwest (fig. 4.1). It lies on the flanks of the dry Ilsham valley and underlies a terrace on the flank of Lincombe Hill which is a fragment of a much more extensive surface, further remnants of which can be seen to the northwest. The cave was resurveyed for this study (Proctor and Smart 1989) and has a total passage length of 934 m (fig. 4.2). It comprises an extensive network of
Figure 4.1.
Kent's Cavern location map.
roughly horizontal passages, which are predominantly phreatic in origin.

Entrances to Kent’s Cavern have been formed where the trunk routes have been intersected by surface erosion: there is evidence also that in the Bear’s Den roof collapse has opened up a shaft to the surface above. Four entrances have been open in historic times. The two present entrances were open before excavation began, and two entrances below them into Smerdon’s Passage were cleared of Pleistocene sediments by Pengelly (1884): the Smerdon’s Passage entrances now lie deeply buried beneath excavation spoil. Three more entrances remain choked with Pleistocene sediments at the ends of the High Level Chamber and Rocky Chamber, and in the roof of the Bear’s Den. Several of the entrances have been important as sources of sediment and are more fully described below.

The cave has a very long history, including at least 15 excavations (Campbell and Sampson 1971), the most important of which are summarised below. The first excavation dates back to Thomas Northmore in 1824, who conducted a minor dig in recent sediments near the present entrances. The first person to penetrate to the Pleistocene levels beneath appears to have been McEnery in 1825-6 and 1829. He found worked flints lying in direct association with bones and teeth of extinct mammals, beneath an undisturbed speleothem floor. Such a discovery contradicted the prevailing theological and
scientific thought of the time and McEnery withheld his results, which were only published in full some forty years later by Pengelly (1869).

The association of man and Pleistocene fauna was demonstrated by Pengelly in 1858 when he excavated Brixham Cavern on the other side of Torbay (Pengelly 1874). In 1865 he turned to Kent's Cavern to excavate under the auspices of the British Association and gather further evidence. Pengelly's excavations in Kent's Cavern were on a massive scale and were to occupy 15 years. Unusually for a worker of the time, he used a grid system, excavating blocks one by three feet across, and a foot deep (30 by 90 by 30 cm). The finds from each block were labelled and recorded and their position within the cave can now be reconstructed with a precision unusual for this period. Unfortunately his care in positional recording was not matched by his enthusiasm for describing the nature of the deposits, and he provided only the most basic account of the sediments he excavated. Proceeding in this fashion, he dug the whole cave to a depth of four feet (1.2 m), and the Long Arcade to a depth of 9 feet (2.7 m) (Pengelly 1884).

No more work was carried out until 1926-1940, when members of the Torquay Natural History Society excavated extensively, mainly in and around the Vestibule, where they reached a depth of around 5 m (Keith et al. 1926-1938, Beynon et al. 1929, Smith 1940). Unfortunately (but
typically of the early 20th century) their excavation techniques were deplorable, with standards of recording below those used by Pengelly 50 years earlier.

No further excavations were carried out in the cave although Campbell and Sampson (1971) reassessed the cave and provided a useful summary of its stratigraphy and palaeolithic industries. The cave is currently the subject of an ongoing multidisciplinary investigation under the auspices of the Kent's Cavern Advisory Committee, with permission and partial funding from Kent's Cavern Ltd. This covers all aspects of the geology and archaeology of the site, of which the work described here forms part.

4.2. The Sediments.

The volume of Pleistocene deposits contained in Kent's Cavern is vast in comparison with other cavern deposits elsewhere in southwest England. Most of the 934 m of known passages contained fossiliferous sediments. Pengelly (1884) established a basic stratigraphic scheme comprising a sequence of: Breccia, Crystalline Stalagmite, Cave Earth, Granular Stalagmite and Black Mould (figs 4.4, 4.5). These units have traditionally been portrayed as a simple vertical sequence. However Straw (1983) has pointed out that Pengelly's descriptions show that the sediments were very unevenly distributed,
with significant differences between the outer (northeast) and inner (southwest) ends of the cave. Other authors have provided basic descriptions of the more obvious units recognisable in the field, and have proposed further units predating the Breccia (Pengelly 1884, Keith et al. 1926-1938, Campbell and Sampson 1971). However, none of them has made any serious attempt to describe their lithology and interpret the depositional environment, and the sediments have remained poorly known.

For this study, examination and mapping of the sediment remnants was undertaken over much of the cave, to establish their nature and distribution and to provide a framework for interpretation. In addition selected sites were sampled to provide material for sedimentary analysis (fig. 4.3). Sample sizes were approximately 1-2 kg. This is much smaller than that required to accurately quantify coarse grained sediments (Gale and Hoare 1992) but permission to collect larger samples was not given, and the necessary sample size would in any case have been prohibitively large. In one case (KC73, fig. 4.10), large boulders in the sediment far exceeded the sample size: here the samples only record the nature of the sediment between the boulders. The samples were analysed for clast orientation and lithology, and the particle size distribution. Clast orientation was measured by recording the bearing and dip of the long axis of each clast (>25mm) as it was excavated. Particle size distribution
analysis was carried out at Exeter University Geography Department, by dry sieving of the >63 μm fraction, and laser granulometry of the <63 μm fraction.

This work provides the first detailed description and interpretation of the sediments. It has confirmed that the basic units described by Pengelly represent distinctive, mappable stratigraphic units: thus they are retained here. However the sediments are considerably more complex than described by him or later authors, and mapping has revealed some major errors in previous interpretation. The stratigraphic units are described below. Their general distribution is summarised in figs. 4.3, 4.4, 4.5, 4.6, 4.9.

(a) **Little Oven Gravel**: sediment possibly predating the Breccia occurs beneath the speleothem floor in the Little Oven, a high level passage connecting the Long Arcade with the Labyrinth (fig. 4.4). No fresh sediment face is exposed: the deposit has never been excavated. The exposed surface of the sediment comprises clean sandstone gravel, but finer material may be present in the fresh sediment. This deposit has been overlooked by previous workers and forms a small remnant high above any other sediment in the cave.

(b) **Breccia**: a conglomerate occurring as thick gently sloping deposits extending over most of the passages at the southwest end of the cave, and capped by Crystalline
Figure 4.3.

Locations of the sediment elevations, sediment sampling sites and speleothem sampling sites.
Figure 4.4.

Elevation of the sediments from the High Level Chamber to the Vestibule. Locations of the figured sediment sections are shown in fig. 4.3.
Figure 4.5.

Elevations of the sediments in the Bear’s Den area. Locations of the figured sediment sections are shown in fig. 4.3.
Stalagmite (figs. 4.4, 4.5, 4.6). To the northeast, the overlying Crystalline Stalagmite had been broken up and the Breccia eroded away (figs. 4.4, 4.6). The former extension of the Breccia into this area is suggested by the presence of remnants of Crystalline Stalagmite floors (notably in the Long Arcade and the Gallery) left hanging high up on the cave walls. The Long Arcade remnants have sandstone cobbles and bone cemented to their bases suggesting that they originally grew on top of the Breccia like the areas of intact floor elsewhere in the cave, since when the floor has been broken up and removed, and a considerable quantity of the deposit eroded from beneath.

Numerous sections of the Breccia up to around 2.5 m in thickness survive, although some are preserved only as thin skins of sediment left on the walls by Pengelly. In many sections little or no structure is visible, the Breccia forming an apparently homogeneous deposit or showing only vague signs of bedding, defined by variations in clast size. However this apparent homogeneity may reflect more the poor state of the sections (dirty and often very thin) and the difficulty of distinguishing lithologically similar units than any real lack of structure. In clean exposures in the Long Arcade and the Bear's Den the deposit can be seen to comprise a series of thick beds (generally between 0.3 m and 0.6 m). The beds are generally subhorizontal, but at one site in the Long Arcade (KC16, fig. 4.3) they have
Figure 4.6.

Distribution of the Breccia, based on mapping by the author and Pengelly (1884).
become folded by postdepositional movement of the sediment.

Samples of the Breccia were taken in the Long Arcade and the Bear's Den (fig. 4.3). The sediment is typically a very poorly sorted conglomerate (fig. 4.7) comprising cobbles up to around 20 cm in size, matrix supported in a dense clayey matrix. Little or no fabric is visible, the clast orientation appearing to be chaotic or weakly subhorizontal (fig. 4.8): individual beds are generally quite homogeneous. In places the sediment consists largely of cobbles and gravel with much less fine material (e.g. KCl7c, fig. 4.7). This better sorted variant can be seen to grade laterally into typical Breccia in the Bear's Den, and sometimes occurs beneath heavy roof drips now marked by speleothem bosses above the Breccia, suggesting it can be attributed to postdepositional washing out of the fine material from the sediment. The clasts comprise almost exclusively Devonian sandstone, siltstone, slate and vein quartz (table 4.1). The sandstone, quartz and some slate clasts are generally angular to subangular: there is also much very fresh angular slate. Limestone is extremely rare. There is significant compositional variation between beds. Apart from the variations in proportions of larger clasts given in table 4.1, some beds can be seen in the field to contain large amounts of fine angular slate debris.
### TABLE 4.1.
Clast lithology of the Breccia. Figures give the number of clasts (>25 mm) of the given lithology in each sample.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Limestone</th>
<th>Sandstone</th>
<th>Siltstone</th>
<th>Slate</th>
<th>Quartz</th>
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<td>10</td>
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<td>16</td>
<td>9</td>
<td>3</td>
</tr>
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<td>8</td>
<td>4</td>
<td>1</td>
<td>-</td>
</tr>
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<td>-</td>
<td>6</td>
<td>6</td>
<td>4</td>
<td>6</td>
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</tbody>
</table>

### TABLE 4.2.
Clast lithology of the Cave Earth in the Wolf's Cave section (KC73). Figures give the number of clasts (>25 mm) of the given lithology in each sample.

<table>
<thead>
<tr>
<th>Sample</th>
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<th>Sandstone</th>
<th>Siltstone</th>
<th>Slate</th>
<th>Calcite</th>
<th>Quartz</th>
<th>Bone</th>
<th>Speleothem</th>
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<tr>
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<td>-</td>
<td>-</td>
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<td>-</td>
</tr>
<tr>
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<td>-</td>
<td>40</td>
<td>14</td>
<td>11</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

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The conglomeratic beds are often separated by much thinner (usually <0.1 m) silty/clayey beds and lenses. These units contain few or no large clasts. At one site in the Long Arcade (KC16) a bed of fine sediment attains a thickness of around 30 centimetres.

(c) Crystalline Stalagmite; a speleothem floor capping the Breccia in most of the passages at the southwest end of the cave, up to the Long Arcade and the Southwest Chamber. It varies from 0 to over 2 m in thickness (figs 4.4, 4.5), and is composed of clean, hard coarsely crystalline calcite. Except where it is thickest the Crystalline Stalagmite shows evidence of postdepositional disruption in the form of cracking and displacement of broken blocks. The floor is cracked in most parts of the cave. Extensive erosion has occurred in the High Level Chamber, the Long Arcade and the Southwest Chamber, largely destroying the floor in these areas.

Remnants of the Crystalline Stalagmite occur in the Wolf's Cave, the Long Arcade and the Gallery, showing that it once extended more widely through the east end of the cave. The Gallery and Long Arcade remnants are located high on the walls above the present top of the sediments (fig. 4.4). Some at least of these remnants appear to have grown on top of Breccia which has since eroded away (see above).
(d) **Cave Earth**: overlying the Crystalline Stalagmite, or where it has been eroded away, lying directly on the Breccia, is the Cave Earth. Three major facies are recognisable within the Cave Earth. At its base is a deposit comprising material very similar to the Breccia. This was described but not named by Pengelly (1884), but Keith *et al.* (1932a) referred to it as a 'Staddon Grit,' because of the sandstone clasts therein, an unfortunate choice in view of the established use of this name for the Lower Devonian rock type most commonly represented as clasts within the sediment. This unit is called the Wash Facies here. It is substantially different from the rest of the Cave Earth and should perhaps be distinguished as a separate unit. Within the main Cave Earth, two closely related facies are represented, which grade into each other: Loamy Cave Earth and Stony Cave Earth (Pengelly 1884, Campbell and Sampson 1971).

The Cave Earth forms very thick wedges of sediment at the present entrances to the cave. Smaller sediment wedges occur at entrances (now blocked) at the lower end of the Rocky Chamber and the top of the High Level Chamber (figs. 4.4, 4.9). The latter deposit was described by Pengelly (1884) as Breccia but it is lithologically like other exposures of Loamy Cave Earth and recent examination of the fauna confirms this identification (see below). A very thin layer of Loamy Cave Earth extends much more widely mantling the older deposits (figs. 4.4, 4.9).
The Cave Earth sequences of most interest are the thick sediment wedges inside the present entrances. This area of the cave has been very extensively excavated; virtually the only significant unexcavated remnant of these thick wedges is a small area in the Wolf's Cave (KC73, figs. 4.4, 4.10). This preserves a condensed sequence of the entire thickness of the Cave Earth and was sampled jointly with P.J. Berridge who excavated samples KC73 a-l, and collected field data on clast size and orientation for these samples. Excavation of the remaining samples, and laboratory analysis and recovery of microfauna for all samples, was carried out by the author. This sequence contains examples of the Wash Facies and Loamy Cave Earth. No good sections of Stony Cave Earth remain to be sampled but small remnants are visible on the walls in the Passage of Urns and the Sloping Chamber.

(d.i) Wash Facies: the basal unit of the Cave Earth in the High Level Chamber, the Charcoal Cave, the Wolf's Cave, and the Sally Ports. The Wash Facies forms the basal 30 cm of the Wolf's Cave sample section (samples KC73 m,n,or,o, fig. 4.10).

The Wash Facies forms a bedded sediment containing large quantities of subangular cobbles in a matrix of sand, silt and clay. The deposit as a whole is very poorly sorted (fig. 4.11) but in field section individual beds
Figure 4.10. Cave Earth; the Wolf’s Cave section (KC73). Location of the section is shown in fig. 4.3.

(a) General view of the section.

(b) Detailed view of the sampled sediment column.
are much better sorted, with stone lines separated by beds of finer sediment. The cobbles within the stone lines are generally clast supported. It shows a rather chaotic clast orientation (fig. 4.12), but possible imbrication is visible in the sections in places. The clasts comprise Devonian sandstone, siltstone, slate and quartz (table 4.2). Although the composition is rather similar to the Breccia, it differs from that deposit in its less dense matrix, clear fabric with easily visible minor bedding and clast supported cobbles.

(d.ii) Loamy/Stony Cave Earth: the major unit of Cave Earth, forming the bulk of the deposit both in the thick sediment wedges at the entrances, and also thin spreads of sediment on top of the Breccia and Crystalline Stalagmite deep into the cave. In the Wolf's Cave section Loamy Cave Earth forms the top 0.55 metre of the sampled section (samples KC73 a-l).

The unit comprises silty clay with scattered matrix supported large clasts, and is very poorly sorted (fig. 4.11). The clasts comprise mostly limestone and sandstone, or bone, (table 4.2) and show a very weak subhorizontal preferred orientation (fig. 4.12). There is no clear bedding on the small scale, the sediments generally consisting of a fairly loose pellet earth. However large scale bedding is apparent, defined by a sequence of flint industries (Campbell and Sampson 1971), and by the proportion and lithology of clasts. In the
Wolf's Cave section the clasts comprise mostly sandstone in the lower part of the unit, but halfway up (sample KC73F) there is a sudden rise in the number of angular limestone clasts (table 4.2). Bone is abundant and generally very well preserved. Many of the bones show teeth marks, and coprolites containing very large quantities of crushed bone are also abundant. A bed of dark clumps of microfaunal bones is present at the level of sample KC73f, identified by A.P.Currant and A.Lister (pers. comm.) as an owl pellet horizon (see below).

The upper layers of Cave Earth remnants in the Vestibule and Great Chamber contain large quantities of limestone debris. In the Passage of Urns, limestone debris comprised most of the sediment: remnants can be seen to comprise clast supported angular limestone fragments with a small amount of silty clay matrix and voids between. This limestone rich facies is the Stony Cave Earth of Campbell and Sampson (1971).

(e) Granular Stalagmite; a speleothem floor overlying the Cave Earth or where it is absent, lying directly on top of the Crystalline Stalagmite (fig. 4.4). Near the present entrances it is a soft tufaceous speleothem typical of near entrance speleothem deposits, but deeper into the cave it is more massive and comes to resemble the Crystalline Stalagmite. Where the two occur in juxtaposition they can sometimes be distinguished because the lower Crystalline Stalagmite has been broken up and
has a weathered upper surface showing a vuggy texture and Fe-Mn staining (for instance at Hedge's Boss in the Cave of Inscriptions). The Granular Stalagmite is up to 1.6 m thick at the entrance to the Long Arcade, but is absent in some areas of the cave, such as the Great Chamber where the Cave Earth was exposed (Pengelly 1884).

(f) **Black Mould**: this comprised a soft dark earth resembling modern topsoil. It was completely removed by Pengelly (1884), and the only remnants visible now are traces on the walls of the Vestibule. The Black Mould occupied only close to the modern entrances around the Vestibule and Great Chamber and contained abundant debris of human habitation extending into historical times. The composition of the deposit and evidence of later prehistoric and historic human habitation clearly identify it as a Holocene cave earth and therefore outside the scope of this thesis.

(g) **Angular blocks of limestone**: in the Great Chamber and Vestibule Pengelly (1884) reported piles of limestone blocks overlying the Granular Stalagmite, and in places the Black Mould. These have now been removed but suggest that roof/wall collapse continued into the Holocene.

In addition to these units others have been proposed, mostly purporting to predate the Breccia. Keith et al. (1931) reported fine silt underlying the Breccia in the Water Gallery. This is not now exposed but the proven
presence of laminated silts within the Breccia raises the question of whether this sediment was actually a separate underlying unit. Campbell and Sampson (1971) also assigned a pre-Breccia age to 'Red Sands' in the Gallery, although they gave no good reason for doing so. These are still exposed in the Gallery where they underlie Loamy Cave Earth, and are here mapped as part of the Cave Earth Wash Facies: they in fact lie considerably higher than the Breccia in the adjacent Charcoal Cave. Pengelly (1884) reported speleothem fragments incorporated into the Bear's Den Breccia, which he thought might predate it. However, speleothems occur interbedded with Breccia in the Bear's Den and the fragments could be derived from this source.

There is no obvious route (such as a hole in the roof) by which the Little Oven Gravel could have been emplaced during or after the emplacement of the other sediments. It may represent a remnant of ancient stream deposited gravels dating from the active phase of cave development. Excavation of this remnant might be useful in determining whether the structure of the fresh sediment is consistent with such an interpretation.

A number of features of the Breccia, including thick structureless beds, very poor sorting, chaotic to subhorizontal clast orientation and matrix support are all features typical of subaerial debris flows, suggesting it was emplaced by this mechanism (Fisher
The gross morphology of the Breccia, forming thick gently sloping deposits (figs. 4.4, 4.5, 4.6), also supports a debris flow origin (Pierson 1980, Lawson 1982). The occurrence of numerous beds of around 0.3-0.6 m in thickness suggests multiple flows occurred, separated by quiescent periods with little or no flow activity. The thin units of fine bedded sediment are consistent with this interpretation as the waterlogged conditions necessary for debris flow emplacement is generally accompanied by small streams. Some of the finer clayey units could have been the result of deposition under low flow conditions when the debris was not mobilised, but some reworking or inwash of fine sediment occurred. In one area, the Bear’s Den, the uppermost units of Breccia occur interbedded with speleothem representing the lowermost Crystalline Stalagmite (fig. 4.5), implying that the interval between flows might in some cases have been substantial, of the order of hundreds or thousands of years.

The Breccia slopes down from three points, the Bear’s Den, spreading out into the adjacent passages (the Bear’s Den Breccia), the High Level Chamber, sloping down into the Long Arcade (the Long Arcade Breccia), and the Great Oven, sloping down to join the Breccia from the High Level Chamber (the Great Oven Breccia) (figs. 4.4, 4.5, 4.6). Given that debris flows move downhill this suggests that the Breccia probably entered the cave at three points. The three flows appear to be lithologically
similar (table 4.1), but confirmation of their existence as separate flows comes from two sources: the distribution of archaeological finds, and the geomorphology and location of entrances. Of the three proposed flows only two, the Bear's Den and High Level Chamber/Long Arcade flows are important: the much smaller Great Oven flow will not be further considered.

A plot of Pengelly's flint finds (P.J. Berridge pers. comm.), shows the two main flows as clearly distinct. The Long Arcade flow is full of artefacts, whereas the Bear's Den flow only has a few, and the junction between these two contrasting abundances occurs where the slope morphology of the deposits suggests it should, at the north end of the Labyrinth.

Each flow comprises almost entirely allochthonous elements, such as sandstone and slate, and must have been derived from outside the cave. This implies that there were entrances at the putative sources. The source of the Long Arcade Breccia, in the High Level Chamber, is known to be a blocked entrance. It lies at high level, and Pengelly (1984) stopped work here when the roof and walls became unstable and he could clearly hear sounds made outside the cave, showing that he was very close to the surface. The source of the Bear's Den Breccia is less obvious. The Breccia here appears to have flowed from an area now occupied by a huge speleothem boss some 9 m across, which reaches to the roof on the southwest side
of the Bear's Den. The roof visible up to the edge of the boss is intact with no signs of collapse. But beneath the boss, excavation has revealed a substantial pile of collapse talus buried in the Breccia. This implies major roof collapse occurred in the region now occupied by the boss, suggesting that there is a blocked hole in the roof here: the surface is only a few metres above the cave. There may have been a roof aven here, like the one still visible a few metres away in the Great Oven. If the surface intersected such an aven, collapse of the walls could have enlarged it into a substantial shaft.

These blocked high level entrances open onto the terrace overlying the cave and this is probably the major source of the sediment. The Breccia contains clasts from two sources: very fresh angular slate which has suffered a minimum of transport: and a mixed suite of subangular sandstone, quartz and slate gravel which has suffered appreciable erosion and rounding. It is highly implausible that the latter could have become so rounded by debris flow emplacement alone. This suggests it is reworked from a pre-existing sediment body. The terrace overlying the cave appears to be devoid of such sediment now but the obvious inference would be that at the time of deposition alluvial sediments remained on the terrace and formed the major source of sediment for the Breccia. The rock types present in this rounded material all crop.out extensively in the Torquay district, supporting such an origin. However, it is surprising that there is
so little limestone in the Breccia since there are numerous outcrops in the area (fig. 4.1) and its presence in the source alluvium would be expected. Possibly this alluvium had a very local source in the predominantly slate and sandstone outcrops to the west; alternatively it might have been an ancient terrace remnant from which the limestone clasts had been lost by solution. The very fresh angular slate in the Breccia suggests freshly eroded sediment was also contributed, possibly material washed or soliflucted onto the terrace from slate outcrops on the adjacent slopes of Lincombe Hill.

These entrances are likely to have been represented on the surface above as dolines. They may never have been open: the passages down into the cave may have remained choked with sediment that periodically slumped down into the passages below. Unless the alluvium was very thick, sediment must have been supplied to the entrances from the surrounding surface, to account for the large volumes deposited within the cave. This might indicate a cold climate with extensive frost weathering and solifluction during the deposition of the Breccia: the presence not only of material of presumed alluvial origin in the Breccia but also fresh slate from nearby hillslopes suggests considerable sediment mobility on the surface. In such conditions the depressions associated with the high level entrances could have been continually supplied with sediment. Destabilisation by the build-up of sediment and by waterlogging during periods of heavy rain
or snow melt, could have resulted in periodic slumping of the sediment into the cave as debris flows (Savage 1969).

The Crystalline Stalagmite is a typical deep cave speleothem floor. The sometimes very substantial thickness of speleothem suggests that its deposition may have lasted a considerable time. There is no evidence of clastic sedimentation at any time during the deposition of the Crystalline Stalagmite, suggesting that a lengthy hiatus in clastic deposition occurred. Together with the deep cave nature of the speleothem, this implies that the cave was sealed and had no open entrances during this period.

The start of Cave Earth deposition is marked by a period of erosion. Features dating from this time include the break-up of the Crystalline Stalagmite, reworking of older sediments, and opening up of entrances. Some initial cracking of the Crystalline Stalagmite floor is likely to have resulted from subsidence due to compaction of the underlying Breccia. The wholesale removal of the Crystalline Stalagmite and of large quantities of Breccia in some parts of the cave suggests some agency such as a stream was also involved. This is also suggested by the presence of a water eroded notch in a speleothem boss in the Cave of Inscriptions. Such a stream (or streams) could have eroded away the uncedmented Breccia from beneath the Crystalline Stalagmite, undermining the floor and causing further cracking and collapse. At the front
of the cave, very large quantities of sediment may have been removed, as indicated by the Crystalline Stalagmite floor remnants high above the present top of the Breccia in the Long Arcade and the Gallery.

The clast lithology of the Cave Earth Wash Facies is similar to the Breccia, dominated by sandstone, siltstone, slate and quartz veinstone, suggesting it represents material reworked from the Breccia (table 4.2). Like the Breccia, the Wash Facies is very poorly sorted (fig. 4.11), suggesting minimal reworking and sorting of the bulk sediment, although fine and coarser material have been sorted into separate beds. These features are consistent with the distribution of the Wash Facies which occurs close to or downslope from areas where the Breccia has been eroded. The fine bedding, sorting of individual beds and possible imbrication indicate the unit is water deposited, probably by a stream which showed very considerable variations in flow. Thus this deposit provides further evidence for a stream flowing through the cave at this time.

Widespread erosion in the High Level Chamber suggests that the stream (or streams) entered the cave at high level. The cave appears already to have been higher than the adjacent valleys (low level entrances in Smerdon’s Passage and the Rocky Chamber were opened into these valleys, probably at this time): the most plausible source for the water is probably snow melt derived from
the terrace and the hillslope above. Such a source would be consistent with the variable flow regime suggested by the nature of the Cave Earth Wash Facies. The reason that large volumes of water entered the cave at this time might lie with the disposition of surface deposits above, which could have caused melt water to collect on the area above the cave. This interpretation implies that this period of erosion and opening of entrances took place during a cold phase. By washing out ancient sediments, this erosive phase was probably responsible for the opening of the entrances which subsequently became sites for the deposition of Loamy Cave Earth.

The presence of chewed bone and coprolites in the Loamy Cave Earth suggests the cave was a carnivore den during the deposition of this unit and the presence of worked flint, and hearths in the Vestibule (see below), indicates that man was also present. This implies that it was deposited in subaerial conditions, and with the presence of bedding and preservation of delicate fauna in very good condition also suggests that it accumulated slowly. These features, together with the poor sorting and loose fabric suggest the Loamy Cave Earth is a typical cave earth deposited slowly by a combination of soil creep, wash, roof or wall collapse and animal activity (Laville 1976, Collcutt et al. 1981, Collcutt 1986). The loose pelleted texture suggests it has been extensively bioturbated, destroying much of the original bedding: this may be associated with the use as an animal
den, which would have supported a flourishing invertebrate fauna.

The presence of thick sediment wedges extending in from the present entrances suggests that these entrances acted as major inputs of fine material reworked from soils on the surface above (Griffiths and Lee 1989). Similar wedges in the High Level Chamber, Rocky Chamber and probably Smerdon's Passage, suggest that entrances into these passages acted as similar sediment sources. These entrances appear to have been smaller and became choked as Cave Earth was deposited. Thin spreads of Loamy Cave Earth also occur deep into the cave. Here the sediment appears to have been washed in through cracks in the roof (Bull 1981): similar sediment can be seen still to be washing in through roof joints at the present day.

The sandstone in the lower part of the Loamy Cave Earth is probably derived from the Breccia like that in the underlying Wash Facies (or reworked from the Wash Facies). In contrast, the abundant limestone in the upper part of the deposit is very angular and probably represents collapse debris derived from the walls and roof, suggesting that collapse increased in importance during its deposition. In the Vestibule, Great Chamber and Passage of Urns the upper layers are very rich in limestone debris, forming the Stony Cave Earth. Its widespread occurrence forming the uppermost Cave Earth in the outer part of the cave implies that wall and roof
collapse became important late in the deposition of the Cave Earth. The deposition of the Granular Stalagmite immediately above implies a further change in conditions which terminated the deposition of the Cave Earth; these are further discussed below.

4.3. Fauna, Archaeology and Palynology.

The Breccia and Cave Earth have both yielded faunal material and artefacts. Of the previous workers Pengelly was the most important: he not only excavated more extensively than any other worker, he was the only one to record the provenance of each find in detail. The lack of any precise information regarding provenance makes the material recovered in the Torquay Natural History Society excavations of very limited use (P.J.Berridge, R.Jacobi pers. comm.). Old finds comprise mostly megafauna and flints; very little microfauna was recovered and that which survives is not accompanied by locality details: it is ignored here as useless. During the present work microfauna has been recovered from the Breccia in the Bear's Den and the Water Gallery, and the Cave Earth in the Wolf's Cave and the High Level Chamber.

In the Breccia Pengelly (1884) recorded a limited fauna including Ursus sp. (bear), Felis leo (lion), Alopex or Vulpes sp. (fox), and an indeterminate deer. Fox, lion and deer were very rare: no material referrable to them
and clearly derived from the Breccia has been located in museum collections despite extensive searches (P.J.Berridge pers. comm.). All three species were restricted to areas where the Crystalline Stalagmite had been eroded away, so the possibility that these represent late intrusions cannot be ignored. Another species often supposed to come from this deposit is *Homotherium latidens* (sabre-tooth cat). However the excavation records of McEnery and Pengelly (Pengelly 1869, 1884) make it quite clear that these were recovered from the Cave Earth. Thus reliable records of the Breccia megafauna comprise only *Ursus*. The Breccia also contains an Acheulian (lower Palaeolithic) industry characterised by handaxes and a variety of other tool types (Campbell and Sampson 1971, Roe 1981). As noted above the distribution of these finds is related to the two main routes for debris flows. The Long Arcade Breccia contains large numbers of implements but little (usually poorly preserved) bone. The Bear’s Den Breccia contains fewer implements but much more abundant, better preserved faunal material (P.J.Berridge, M.Bishop pers. comm.).

Analysis of the fauna of the Bear’s Den Breccia is being carried out by M.J.Bishop, who has also recently recovered microfauna from this deposit with P.J.Berridge (table 4.3). The bears belong to the early Middle Pleistocene species *Ursus aeningeri*. This species occurs in the Cromerian and Westbury Interglacials (Bishop 1982): the Kent’s Cavern material is a late type, more
advanced than Cromerian (West Runton), and is very similar to the Westbury *U. deningeri* suggesting an age close to that interglacial (M. Bishop pers. comm.). Similar conclusions can be drawn from the microfauna, comprising the voles *Pitymys gregaloides, Arvicola cantiana* and *Microtus oeconomus*. This assemblage is again characteristic of the Westbury Interglacial (Sutcliffe and Kowalski 1976, Bishop 1982). However it should be noted that the interglacial itself may not be represented here. None of the species involved are thought to be interglacial indicators, and such limited evidence as is available from the sediments is more in favour of a cold climate. The deposit could very easily date from a cold stage close in age to the Westbury Interglacial.

The *Ursus deningeri* contain a mix of ages including very young animals and this, with the very restricted faunal composition suggest they were using the cave as a hibernaculum and breeding site (M.J. Bishop pers. comm.). Their remains in the Bear's Den area are well preserved and occur in rich concentrations at the top of the Breccia and as more scattered material (sometimes forming rich pockets) within it. Rodents are commonest in areas rich in *U. deningeri*. This suggests the animals used this part of the cave, and successive flows incorporated their remains. The artefacts, by contrast, occur scattered throughout the Breccia and this, along with extensive evidence of mechanical damage (R. Jacobi pers. comm.), suggests they were probably carried into the cave by the
<table>
<thead>
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<tbody>
<tr>
<td>Ursus deningeri</td>
</tr>
<tr>
<td>Pitymys gregaloides</td>
</tr>
<tr>
<td>Arvicola cantiana</td>
</tr>
<tr>
<td>Microtus oeconomus</td>
</tr>
</tbody>
</table>

**TABLE 4.3.**

Fauna of the Breccia (M. Bishop pers. comm.).

<table>
<thead>
<tr>
<th>Species</th>
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<tbody>
<tr>
<td>Crocuta crocuta</td>
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<tr>
<td>Homotherium latidens</td>
</tr>
<tr>
<td>Felis leo</td>
</tr>
<tr>
<td>Gulo gulo ('rare')</td>
</tr>
<tr>
<td>Meles meles</td>
</tr>
<tr>
<td>Canis lupus</td>
</tr>
<tr>
<td>Vulpes vulpes</td>
</tr>
<tr>
<td>Ursus arctos</td>
</tr>
<tr>
<td>Mammuthus primegenius</td>
</tr>
<tr>
<td>Coelodonta antiquitatis</td>
</tr>
<tr>
<td>Equus ferus</td>
</tr>
<tr>
<td>Cervus/Rangifer sp.</td>
</tr>
<tr>
<td>Megaloceros giganteus</td>
</tr>
<tr>
<td>Bison/Bos sp.</td>
</tr>
<tr>
<td>Castor fiber ('rare')</td>
</tr>
</tbody>
</table>

**TABLE 4.4.**

Megafauna of the Cave Earth, from Campbell and Sampson (1971), based on Pengelly's unpublished diaries.
debris flows. Thus their makers were probably living on the flat ground above rather than in the passages in which the artefacts were found. The large number of artefacts in the Long Arcade Breccia would seem to indicate intense activity in the source region of this flow: perhaps the entrance through which the flow entered formed a convenient sheltered hollow or rock shelter which was used for habitation. There is certainly no evidence for Acheulian hunting activities in the cave as suggested by Campbell and Sampson (1971).

The Cave Earth has a much richer fauna, accompanied by a series of Middle and Upper Palaeolithic industries. Both Pengelly (1884) and Keith (1932a, 1932b) note that fauna is scarce in the Wash Facies: neither gives details beyond noting that the fauna is similar to that in the overlying Loamy/Stony Cave Earth. A single Acheulian handaxe was reported from the Wash Facies of the Wolf's cave by Keith et al. (1932b); this is believed to be derived from the Breccia. The Loamy/Stony Cave Earth has a long faunal list dominated by Crocuta (spotted hyaena) (table 4.4). The presence of much coprolitic material referrable to this species and bone fragments showing characteristic chew marks and evidence of digestion shows that Crocuta was denning in the cave. The condition of their bones suggests that many of the larger species such as Mammuthus (mammoth) and Coelodonta (woolly rhino) were almost certainly prey brought into the cave by Crocuta (A.P. Currant pers. comm., Stuart 1983). Within the thick
Cave Earth sequences in the Vestibule and Great Chamber and adjacent passages, a bedded sequence of Palaeolithic industries has been found, including Middle, Early Upper and Late Upper Paleolithic industries. The last was associated with an extensive hearth, the Black Band, at the top of the Cave Earth in the Vestibule (Campbell and Sampson 1971, Campbell 1977, Roe 1981, P.J.Berridge, R.Jacobi pers. comm.). The fauna and industries of these chambers is currently the subject of investigation by P.Berridge, R.Jacobi and A.Roberts.

Microfauna was recovered and identified by the author from the sample section in the Wolf's Cave (table 4.5), and subsequently checked by A.P.Currant. The lower part of the section, corresponding to the Wash Facies, contained no fauna. The lower Loamy Cave Earth (KC 73 g-1) contains only Microtus. The presence of M. gregalis implies the climate might have been cool. A rich fauna is present in KC73F. This sample contains a layer of black masses of bones, comprising a very diverse range of small mammals, amphibians and reptiles. The bone masses probably represent an owl pellet horizon which would explain the occurrence of discrete masses containing a wide range of species (A.P.Currant, A.Lister pers. comm., Andrews 1990). The species present include a number of warm climate indicators, such as Apodemus (wood mouse), Clethrionomys (bank vole), lizard, and frog or toad. From this level to the top of the Cave Earth the fauna is rich with a mixture of warm and cold climate indicators,
| Sample    | Sorex sp. | Lepus sp. | Ochotonapusa | Clethrionomys glareolus | Microtus sp. | Microtus agrestis | Microtus oeconomus | Microtus gregalis | Arvicola terrestris | Lemmus lemmus | Dicrostonyx torquatus | Apodemus sylvaticus | Lizard | Frog/toad |
|-----------|-----------|-----------|--------------|--------------------------|--------------|-------------------|---------------------|-------------------|---------------------|---------------|----------------------|----------------------|---------|
| KC73A     | X         | X         |              |                          |              |                   |                     |                   |                     |               |                      |                      |         |           |
| KC73B     | X         | X         | X            |                          | X            |                   |                     |                   |                     |               |                      |                      |         | X          |
| KC73C     | X         | X         | X            | X                        | X            |                   |                     |                   |                     |               |                      |                      |         | X          |
| KC73D     | X         | X         |              |                          | X            |                   |                     |                   |                     |               |                      |                      |         | X          |
| KC73E     | X         | X         |              |                          | X            |                   |                     |                   | X                   |               |                      |                      |         | X          |
| KC73F     | X         | X         | X            | X                        | X            |                   |                     |                   | X                   |               |                      |                      |         | X          |
| KC73G     | X         |           |              |                          |              |                   |                     |                   |                     |               |                      |                      |         | X          |
| KC73H     | X         |           | X            |                          |              |                   |                     |                   |                     |               |                      |                      |         | X          |
| KC73I     | X         |           |              |                          |              |                   |                     |                   |                     |               |                      |                      |         | X          |
| KC73J     | X         |           |              |                          |              |                   |                     |                   |                     |               |                      |                      |         | X          |
| KC73K     | X         |           |              |                          |              |                   |                     |                   |                     |               |                      |                      |         |            |
| KC73L     | X         |           |              |                          |              |                   |                     |                   |                     |               |                      |                      |         | X          |
| KC73M     | X         |           |              |                          |              |                   |                     |                   |                     |               |                      |                      |         |            |
| KC73N     | X         |           |              |                          |              |                   |                     |                   |                     |               |                      |                      |         |            |
| KC73O     | X         |           |              |                          |              |                   |                     |                   |                     |               |                      |                      |         |            |
| HLC       | X         | X         | X            |                          |              |                   |                     |                   |                     |               |                      |                      |         |            |

**TABLE 4.5.**

Microfauna of the Cave Earth. KC73, Wolf's Cave section samples; HLC, High Level Chamber sample. Details of the High Level Chamber fauna from P. Berridge (pers. comm.).
including *Apodemus*, *Sorex* (shrew), *Lemmus* (Norway lemming) and *Ochotona* (steppe pika).

The Wolf's Cave samples were too small to yield a significant amount of megafauna, but the sample section lies in the side of a trench within which Pengelly (1884) recorded the typical Cave Earth megafauna with dominant *Crocuta*, and flints referrable to Middle and Late Upper Palaeolithic (and possibly Early Upper Palaeolithic) industries. This fauna shows little zonation, but Keith *et al.* (1930, 1931) noted that in the lower Loamy Cave Earth here, *Equus* (horse) was more abundant than *Crocuta* in contrast to the upper 1.2 m excavated by Pengelly. Pengelly (1884) did record a similar faunal zonation in the adjacent Cave of Rodentia. Too few implements are present to preserve any details of stratification. Pollen was recovered from the Wolf's Cave section by C. Caseldine and J. Hatton (pers. comm.), who found a herbaceous flora indicating cool conditions, showing little variation up the section. A *Crocuta* coprolite within the section was analysed separately and found to contain a similar flora.

The main fauna and industries of the Cave Earth are of typical Middle to Upper Devensian type (Campbell and Sampson 1971, Campbell 1977, Roe 1981, Stuart 1982, 1983). The range of industries imply quite a long sequence from the Middle Devensian to the Late Glacial. Changes in the megafauna might be expected to have
occurred over this period but at present, the location of faunal material within the Cave Earth is too poorly known to recognise any faunal zonation beyond the existence of an Equus rich fauna beneath the Crocuta fauna in the Wolf’s Cave and Cave of Rodentia. One species, Homotherium latidens (sabre-tooth cat), does not belong in this period. It is a Middle Pleistocene species which appears to have been long extinct by the Devensian. Although Homotherium is a plausible component of a Westbury fauna like that found in the Breccia, it is unlikely it was derived from that deposit. Homotherium has never been found in the Breccia (Pengelly 1884). Also, only teeth occur and this, along with their condition (including well preserved delicate canines) is not consistent with reworking from the Breccia. It seems possible that the teeth were brought in as fossils by Palaeolithic occupants, as has been suggested for the same species at Creswell by Stuart (1982). The Wolf’s Cave microfauna is of special interest because of the peculiar mix of cold and interglacial indicators. This is characteristic of the later Late Glacial (A.P. Currant pers. comm.): a similar fauna is known from Broken Cave at Torbryan (A. Roberts pers. comm.). The correlation of the upper part of this sequence with the Late Glacial is quite consistent with the megafauna and industries, which indicate a Middle to Upper Devensian age for this section. The pollen sequence poses something of a puzzle as it shows little evidence of climatic variation. However, in view of the thin condensed nature of the
Wolf's Cave sequence and the evidence of bioturbation provided by the sedimentary structure. C. Caseldine (pers. comm.) has suggested that periods of climatic fluctuation within the Devensian (including the Late Glacial) are simply not resolved.

A different fauna has been obtained by P.J. Berridge from the wedge of Loamy Cave Earth in the High Level Chamber. This was recorded by Pengelly as Breccia, perhaps because the fauna is dominated by Ursus sp.: it may represent a hibernaculum like the Breccia of the Bear's Den. The megafauna has yet to be examined in detail: other species may be present. Microfauna from here was identified by A.P. Currant (pers. comm.) (table 4.5). The species present (the voles Microtus gregalis, M. oeconomus, and the arctic lemming Dicrostonyx torquatus) identify the deposit as dating from a Devensian cold stage.

Extensive industries and fauna were recovered from the Black Mould: however as noted above this of Holocene age and lies outside the scope of this thesis.

4.4. Age of the Deposits.

In order to date the deposits, U-series and ESR dating of associated speleothems was undertaken. Standard U-series and ESR methods were used. Most speleothems were clean and suitable for U-series dating. Three samples had
Th/232Th ratios of less than 20, showing that significant detrital contamination had occurred. The true age of these samples was estimated using correction method 1 (equation 8) of Schwarcz (1980). In all cases the correction was less than 1 standard deviation. For the ESR dating, in situ dosimetry was carried out by placing dosimeters in holes drilled adjacent to the sampling sites, attempting to place the dosimeters at the speleothem-sediment interface. To further explore the radiation environment, additional dosimeters were used, at the speleothem-sediment interface away from sample sites, and in the bulk sediment at least 50 cm below the speleothems.

Dateable speleothem occurs in association with the Breccia in two situations. Through much of the cave the deposit is capped by the thick Crystalline Stalagmite floor, and in the Bear’s Den fragments of an earlier floor occur interbedded with the uppermost Breccia. Four samples of speleothem capping the Breccia have been dated by P.L. Smart, yielding ages of up to 350 ka. The author recalculated these ages to correct for changes in spike calibration and carried out further U-series analyses of samples taken from the floor capping the Breccia and speleothems within the Breccia. Because the ages already obtained suggested the age of the Breccia lay close to the U-series dating limit of around 350 ka, ESR analysis of a series of further samples was also undertaken. Dosimetry and sample preparation for these analyses were
carried out by the author, and ESR spectra measured by I. Podmore and M. Symons (except for KC3-83B2, for which sample preparation and ESR measurement was carried out by P. L. Smart). The speleothem capping the Breccia could only give a minimum age for the deposit. For this reason the dating effort was concentrated in the Bear's Den where speleothem interbedded with the Breccia gives the chance to obtain a date predating the topmost Breccia and faunas. Moreover this was the area where M. J. Bishop (pers. comm.) has identified Westbury type faunas. The Crystalline Stalagmite in the Cave of Inscriptions was also dated to attempt to obtain a minimum age for the Long Arcade Breccia. The sample sites are shown in figs. 4.3, 4.13.

The U-series and ESR dating results are listed in tables 4.6, 4.7. In the Cave of Inscriptions a sample from the base of the Crystalline Stalagmite, KC-90-2, yielded a U-series age of 550 (368-00) and an ESR age of 80 (63-99) ka. KC-90-2D, just above, yielded a U-series age of 410 (337-723) ka, and an ESR age of 91 (78-106) ka. The huge discrepancy between these ages shows that one or both dating techniques has failed (fig. 4.14). The speleothem may be recrystallised, which would have resulted in spuriously old U-series ages (due to uranium leaching) and spuriously young ESR ages (due to resetting of the ESR signal). Although this in theory allows one to get a rough idea of the age range of the speleothem, in
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<th>Th%</th>
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<th>230Th/234U</th>
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<td>KC-90-5B2</td>
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<td>8</td>
<td></td>
<td>0.064</td>
<td>1.135±0.012</td>
<td>1.000±0.027</td>
<td>25.8±2.0</td>
<td>354 (299-468)</td>
<td>-</td>
</tr>
<tr>
<td>6730</td>
<td>KC-90-2AB</td>
<td>36</td>
<td>12</td>
<td></td>
<td>0.044</td>
<td>1.074±0.015</td>
<td>1.021±0.028</td>
<td>28.6±3.0</td>
<td>550 (368-800)</td>
<td>-</td>
</tr>
<tr>
<td>6731</td>
<td>KC-90-6</td>
<td>17</td>
<td>20</td>
<td></td>
<td>0.070</td>
<td>1.177±0.021</td>
<td>0.920±0.023</td>
<td>12.4±0.5</td>
<td>235 (215-260)</td>
<td>228 (207-253)</td>
</tr>
<tr>
<td>6740</td>
<td>KC-90-5B1</td>
<td>6</td>
<td>108</td>
<td></td>
<td>0.092</td>
<td>1.199±0.037</td>
<td>0.944±0.035</td>
<td>17.0±0.4</td>
<td>253 (219-303)</td>
<td>247 (214-297)</td>
</tr>
<tr>
<td>6741</td>
<td>KC-90-3B</td>
<td>77</td>
<td>82</td>
<td></td>
<td>0.017</td>
<td>1.146±0.019</td>
<td>1.062±0.020</td>
<td>21.1±1.0</td>
<td>00 (484-804)</td>
<td>-</td>
</tr>
<tr>
<td>6742</td>
<td>KC-90-2D1</td>
<td>59</td>
<td>48</td>
<td></td>
<td>0.043</td>
<td>1.075±0.015</td>
<td>1.002±0.021</td>
<td>23.7±1.3</td>
<td>410 (337-723)</td>
<td>-</td>
</tr>
<tr>
<td>6757</td>
<td>KC-90-4A2</td>
<td>42</td>
<td>11</td>
<td></td>
<td>0.031</td>
<td>1.158±0.025</td>
<td>0.888±0.040</td>
<td>56.6±20.0</td>
<td>213 (186-249)</td>
<td>-</td>
</tr>
<tr>
<td>6760</td>
<td>KC-91-1</td>
<td>76</td>
<td>22</td>
<td></td>
<td>0.071</td>
<td>1.236±0.018</td>
<td>0.399±0.015</td>
<td>26.8±5.3</td>
<td>53 (50-55)</td>
<td>-</td>
</tr>
<tr>
<td>6761</td>
<td>KC-91-2</td>
<td>39</td>
<td>84</td>
<td></td>
<td>0.022</td>
<td>1.159±0.025</td>
<td>1.771±0.038</td>
<td>43.5±2.4</td>
<td>&gt;00</td>
<td>-</td>
</tr>
</tbody>
</table>

**TABLE 4.6.**

Uranium series analyses from Kent's Cavern.
<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Name</th>
<th>U (μg/g)</th>
<th>AD (Gy)</th>
<th>Ext.DR (mGy/a)</th>
<th>Int.D (Gy)</th>
<th>Age (ka)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Analyzes using standard dosimetry</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6516.0</td>
<td>KC3-83B2</td>
<td>0.036</td>
<td>81.9±5.7</td>
<td>0.344±0.052</td>
<td>4.66</td>
<td>225 (184-278)</td>
</tr>
<tr>
<td>6728.2</td>
<td>KC-90-3A</td>
<td>0.017</td>
<td>181±18</td>
<td>0.526±0.044</td>
<td>4.24</td>
<td>335 (280-401)</td>
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<tr>
<td>6728.9</td>
<td>KC-90-3A</td>
<td>0.017</td>
<td>229±28</td>
<td>0.618±0.052</td>
<td>4.75</td>
<td>363 (295-444)</td>
</tr>
<tr>
<td>6729.8</td>
<td>KC-90-5B2</td>
<td>0.064</td>
<td>184±16</td>
<td>0.526±0.044</td>
<td>14.9</td>
<td>322 (275-376)</td>
</tr>
<tr>
<td>6730.1</td>
<td>KC-90-2AB</td>
<td>0.044</td>
<td>90.0±13.6</td>
<td>1.13 ±0.09</td>
<td>-0.27</td>
<td>80 (63-99)</td>
</tr>
<tr>
<td>6730.6</td>
<td>KC-90-2AB</td>
<td>0.044</td>
<td>87.5±6.8</td>
<td>0.96±0.080</td>
<td>0.15</td>
<td>91 (78-106)</td>
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<tr>
<td>6740.3</td>
<td>KC-90-5B1</td>
<td>0.092</td>
<td>228±22</td>
<td>0.726±0.061</td>
<td>20.0</td>
<td>287 (243-338)</td>
</tr>
<tr>
<td>6741.7</td>
<td>KC-90-3B</td>
<td>0.017</td>
<td>192±17</td>
<td>0.853±0.071</td>
<td>2.25</td>
<td>223 (188-264)</td>
</tr>
<tr>
<td>(b) Bear's Den analyses using Bear's Den average dose</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6516.0</td>
<td>KC3-83B2</td>
<td>0.036</td>
<td>81.9±5.7</td>
<td>0.508±0.186</td>
<td>2.37</td>
<td>157 (112-241)</td>
</tr>
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<td>6728.2</td>
<td>KC-90-3A</td>
<td>0.017</td>
<td>181±18</td>
<td>0.432±0.136</td>
<td>5.53</td>
<td>405 (281-635)</td>
</tr>
<tr>
<td>6728.9</td>
<td>KC-90-3A</td>
<td>0.017</td>
<td>229±28</td>
<td>0.508±0.160</td>
<td>6.19</td>
<td>439 (295-704)</td>
</tr>
<tr>
<td>6729.8</td>
<td>KC-90-5B2</td>
<td>0.064</td>
<td>184±16</td>
<td>0.432±0.136</td>
<td>19.1</td>
<td>382 (275-564)</td>
</tr>
<tr>
<td>6740.3</td>
<td>KC-90-5B1</td>
<td>0.092</td>
<td>229±22</td>
<td>0.597±0.187</td>
<td>25.6</td>
<td>340 (244-503)</td>
</tr>
<tr>
<td>6741.7</td>
<td>KC-90-3B</td>
<td>0.017</td>
<td>192±17</td>
<td>0.701±0.220</td>
<td>3.08</td>
<td>270 (188-424)</td>
</tr>
</tbody>
</table>

**TABLE 4.7.**

ESR analyses from Kent's Cavern. AD, accumulated dose; Ext.DR, external dose rate; Int.D, internal dose.
practice the only limit that can be deduced is that the speleothem is probably over 80-90 ka in age.

A number of samples associated with the Breccia around the large boss in the Bear's Den were dated. ESR dating was complicated here by the discovery of large variations in the environmental dose rate, revealed by the dosimetry at multiple sites described above: a range of 0.54 to 1.02 mGy was measured at dosimeters placed in contact with speleothems (over a 407 day period of dosimetry). This is probably due to the presence of large limestone boulders buried in the sediment, which would contribute a lower gamma radiation dose than the equivalent volume of clastic sediment. This created an additional uncertainty in dating since the samples, which were collected from exposed sediment faces, were 50 cm from the dosimeters (more in the case of KC-90-3: see below): thus the dose actually received by the sample could have been significantly different from that measured at the dosimeter. In addition, since dosimetry was not possible for KC-90-3, the ages for this sample had to be calculated using the nearest dosimeter, adjacent to KC-90-5, so dates from both these speleothems rely upon a single dosimeter. To overcome these problems ages were calculated twice, first using the adjacent dosimeter, and secondly using a mean value (0.79±0.23 mGy over 407 days), derived from all dosimeters placed at the speleothem-sediment interface in the Bear's Den. The
latter age is referred to below as the 'average dose' age.

KC3-833 was the base of the Crystalline Stalagmite floor and had fragments of bone (probably Ursus) cemented into the Breccia directly below it. This sample was dated by P.L. Smart yielding U-series ages of 355 (280-698) and 355 (312-427) ka. ESR dating yielded an age of 225 (184-278) ka (average dose 157 (112-241) ka). Another sample from the base of the floor, KC-90-4, yielded a U-series age of 213 (186-249) ka.

KC-90-3 was a speleothem drape on the side of a boulder. The base of the drape had grown out onto the top of a debris flow and the speleothem had been buried under another flow. Thus this sample predates the topmost Breccia. The Breccia had been removed from around this sample by previous excavation, so the dosimeter at the nearest available site (KC-90-5) was used to calculate the age. The basal growth layer yielded a U-series age of 311 (267-384) and ESR ages of 335 (280-401) ka (average dose 405 (281-635) ka) and 363 (295-444) ka (average dose 439 (296-704) ka). The middle growth layer yielded a U-series age of 484 ka and an ESR age of 223 (188-264) ka (average dose 270 (188-424) ka). KC-90-5 was a large broken speleothem block, also interstratified between Breccia beds. Two samples from a clean growth layer at the middle were dated, the first yielding a U-series age of 247 (214-297) and an ESR age of 287 (243-338) ka.
(average dose 340 (244-503) ka), and the second a U-series age of 354 (299-468) ka and an ESR age of 322 (275-376) ka (average dose 382 (276-564) ka).

In the Bear's Den, in contrast to the Cave of Inscriptions, good agreement was obtained between U-series and ESR ages (fig. 4.14). All the samples, including speleothems within and capping the Breccia produced U-series ages scattered around 350 ka, though with a low precision. These ages fall very close to the practical limit of alpha spectrometric U-series dating, but provide a good minimum age for the deposit of around 350 ka. Although ESR dating was made problematical by the large variations in dose rate described above, the results agree with the U-series ages in suggesting an age of 300-400 ka, although the 'average dose' ages are of very low precision due to the uncertainty in the dose rate. The essentially similar ages obtained for speleothems within and capping the Breccia suggest they might be close in age: given the uncertainty of the ages, a difference of several tens of thousands of years would produce effectively identical ages.

Comparing the results with the oxygen isotope record (Imbrie et al. 1984), the U-series ages indicate that the Breccia is unlikely to be younger than oxygen isotope stage 9 or 10. Defining a maximum age is more problematical, but unless a systematic bias is present in both the U-series and ESR ages the results from
Figure 4.14.

Speleothem dating results associated with the Breccia.

(a) U-series ages, and ESR ages calculated using standard dosimetry.

(b) ESR ages from the Bear's Den, calculated using the Bear's Den average dose.
speleothems within the Breccia suggest the deposit is unlikely to predate an age of around 400 ka. This would imply that it is no older than stage 11, the beginning of which is placed by Imbrie et al. (1984) at 423 ka.

Two samples from the top of the Crystalline Stalagmite in this area of the cave were dated by P.L. Smart (figs. 4.3, 4.13, table 4.6). KC2-83B, from the Water Gallery, yielded an age of 286 (240-373) ka. An age of 115 (111-119) ka was obtained for KC4-83C, the topmost layer of the boss in the Bear's Den. The latter sample is of particular interest since this boss has been cracked like the Crystalline Stalagmite elsewhere in the cave: thus it provides a maximum age for the break-up of this boss. In addition it shows that deposition of clean speleothem continued until around 115 ka, implying that Cave Earth deposition in the Bear's Den began after that time.

Three samples associated with the Cave Earth have been U-series dated (figs. 4.3, 4.13, table 4.6). In the Wolf's Cave a wall remnant of Crystalline Stalagmite, KC-90-6, was buried beneath the Loamy Cave Earth: it yielded an age of 228 (207-253) ka. In the High Level Chamber the Loamy Cave Earth is capped by a speleothem floor, KC-91-1, which was dated by A. Baker to give an age of 53 (50-55) ka. A broken remnant of the Crystalline Stalagmite above this sample (KC-91-2) yielded a greater than infinite age, suggesting it may have been leached.
The age of around 228 ka obtained for KC-90-6 provides a maximum age for the Cave Earth. This is further constrained to around 115 ka by KC4-83C which predates the break up phase that appears to have preceded or accompanied the start of Cave Earth deposition. KC-91-1 provides a minimum age of around 53 ka for the beginning of Cave Earth deposition which is thus constrained to between around 115 and 53 ka. Comparison with the Gower caves suggests a later rather than earlier date. Dating of the faunas at Bacon and Minchin Holes (this thesis) suggests interglacial type faunas may have persisted in the Early Devensian until the end of oxygen isotope stage 5 at around 74 ka. Such warm faunas are not seen in Kent's Cavern implying that Cave Earth deposition began after that time.

KC-91-1 shows that deposition of the High Level Chamber Cave Earth ended by around 53 ka. Within the thick wedges of Cave Earth near the present entrances, the top of the Cave Earth has been well dated by $^{14}$C analysis of bone associated with Upper Palaeolithic industries. Ages of around 12 ka have been obtained for the Late Upper Palaeolithic and 30-40 ka for the Earlier Upper Palaeolithic (including an age of 31 ka for a EUP human jaw) (Campbell and Sampson 1971, Hedges et al. 1989, Jacobi et al. 1986). Clearly in this area of the cave deposition of the Cave Earth continued for much longer than in the High Level Chamber.
The inference that the Cave Earth faunas probably postdate the end of oxygen isotope Stage 5 at around 74 ka implies an age for the High Level Chamber cold fauna of between around 74 to 53 ka. Comparison with the oxygen isotope record (Martinson 1987) suggests it may date from stage 4. Near the entrances the $^{14}C$ ages show that deposition continued through stages 3 and 2 to the end of the Devensian.

4.5. Discussion.

Despite its size and the local complexity of its sediments, the basic stratigraphy of Kent's Cavern is fairly simple: difficulties arise mainly because deposits do not extend uniformly across the cave, and the extent of erosion of early sediments varies from place to place.

The Breccia and Cave Earth form two largely unrelated sequences of fossiliferous clastic sediments separated by the Crystalline Stalagmite. That this speleothem represents a major hiatus in clastic sedimentation has long been suspected by previous workers from comparison of the industries and fauna with other sites (Campbell and Sampson 1971, Sutcliffe and Kowalski 1976). This is confirmed by the U-series ages obtained for the Crystalline Stalagmite, which show that its deposition lasted for a quarter of a million years, from around 350 ka to 115 ka. During this time the entrances appear to
have been blocked, and there is no evidence that clastic sediments or faunal deposits accumulated anywhere in the cave.

Campbell and Sampson (1971) and Sutcliffe and Kowalski (1976) noted that the fauna of the Breccia might indicate a pre-Hoxnian (possibly Westbury) age, leading the former to suggest that the Acheulian industries in the Breccia might be the earliest in Europe. The Breccia is now known to date from around the time of the Westbury Interglacial (see above). Industries associated with Westbury faunas have been identified at two other British sites, at Westbury-sub-Mendip itself (Bishop 1975) and Boxgrove (Roberts 1986): the latter site has also recently yielded a hominid bone (Roberts et al. 1994, Gamble 1994). Thus while the age of the Breccia has been confirmed it is no longer unique. These sites represent the earliest evidence of human occupation positively identified in Britain, giving extra significance to the dates reported here. Unfortunately the debris flow context within which the Kent's Cavern artefacts occur make it almost impossible to make any environmental inferences for the human occupation. Artefacts left by their makers on the terrace above the cave could have remained on the surface for some time before becoming incorporated in the Breccia debris flows and transported inside. Thus although the Breccia was probably emplaced during a cold phase, the human occupation may have occurred rather earlier at a time when the climate was more amenable. By contrast the
*Ursus* dominated fauna is almost certainly contemporaneous with the Breccia, having occupied the cave during its deposition.

Cave Earth deposition appears to have begun when water flowing through the cave eroded older sediments and opened entrances. As noted above the water appears to have entered the cave at high level, suggesting it must have come from the hillslopes above and might represent snow meltwater. The earliest Cave Earth fauna is consistent with this interpretation: the High Level Chamber fauna comprises species characteristic of a cold stage, and has been dated to oxygen isotope stage 4. This fauna is of considerable interest because few faunas from this period have been recognised (A.P. Currant, pers. comm.). The High Level Chamber entrance appears to have become choked with Cave Earth by around 53 ka, ending the deposition of Cave Earth in this part of the cave.

The basal Cave Earth within the thick sequence near the present entrances may be similar in age to the High Level Chamber Cave Earth: possibly the *Equus* dominated fauna recognised by Pengelly (1884) and Keith et al. (1930, 1931) in the lowermost Loamy Cave Earth of the Cave of Rodentia and Wolf's Cave dates from this period.

The main *Crocuta* dominated fauna of the Cave Earth, with its associated Middle and Upper Palaeolithic industries, is a typical Middle to Upper Devensian cave assemblage.
similar faunas and industries are known from other British cave sites, such as Creswell (Jenkinson 1984) and the Wookey Hole ravine caves (this thesis). However Kent's Cavern is unusual in the completeness of the sequence with a stratified series of Middle, Early Upper and Late Upper Palaeolithic occupation horizons. Only Pin Hole at Creswell (Jenkinson 1984) shows a similarly complete sequence: unfortunately like Pin Hole the deposits in Kent's Cavern have been largely destroyed.

An interesting feature of this sequence in the Wolf's Cave is the marked increase in the proportion of limestone debris seen towards the top of the section. Comparison with the fauna suggests this sediment dates from the Late Glacial, implying a marked increase in roof and wall collapse at this time. Other Cave Earth exposures show a similar feature, and the occurrence of large limestone blocks on top of the Black Mould shows that collapse continued into the Holocene. Similar evidence of Late Glacial and Holocene collapse is seen in Torbryan (this thesis, A.Roberts pers. comm.) and contradicts the commonly held supposition that roof/wall collapse is an indicator of cold phases (Laville 1976): clearly the rock remained stable through the Dimlington Stadial but collapse began when the climate began to warm during the Late Glacial. The author has no convincing answer for why this happened, but thawing of permafrost, rapid climate change or the development of vegetation cover might have been involved. The evidence provided by
\(^{14}C\) dates suggests that Cave Earth deposition ceased at the beginning of the Holocene. This probably resulted from the establishment of a vegetation cover, much decreasing sediment mobility outside the cave. The overlying Granular Stalagmite is a typical Holocene speleothem indicative of the warm climatic conditions which followed.
5. THE TORBRYAN CAVES.

5.1. Introduction.

The Torbryan Caves comprise ten short tunnels and rockshelters about 6 km southwest of Newton Abbot in South Devon. The caves are situated in the dry Torbryan valley and are formed in the East Ogwell Limestone, of Middle to Upper Devonian age. The Torbryan valley lies parallel to the course of the Ambrook which runs down a valley on Norden Slate 500 m to the southwest. The main group (Tornewton to Broken Caves), with which this chapter is concerned, lie under the limestone ridge separating the two valleys, and have entrances in low cliffs on the west side of the Torbryan valley: they are fragments of phreatic caves which have been bisected by later valley erosion (fig. 5.1).

The caves were discovered by James Lyon Widger, who carried out excavations in four caves between about 1865 and 1890 (Walker and Sutcliffe 1967). Widger had no scientific training, which prevented him from appreciating the full significance of the thick Pleistocene deposits he encountered. Numerous excavations have been carried out since (Dowie 1925, Carreck 1957, Sutcliffe and Zeuner 1962, Rosenfeld 1964a) and the valley was the site of a British Museum excavation from 1989 to 1992. The work described here was carried out as part of this excavation.
Figure 5.1.

Location map of the Torbryan caves.
T orcourt, Broken, Pulsford and Levaton Caves have all yielded material dating from the Devensian (Dowie 1925, Carreck 1957, Walker and Sutcliffe 1967, A.Roberts pers. comm.) but of far greater significance are the long Pleistocene sequences which occur in Three Holes Cave, Unnamed Cave no. 2 and Tornewton Cave. Sutcliffe (1957) showed that the deposits in Tornewton Cave span a range from the Holocene to before the Ipswichian Interglacial, and more recent work on the fauna has shown that the Aveley Interglacial is also represented at this site (A.P.Currant pers. comm.). Three Holes Cave, better known for its Upper Palaeolithic and later occupations, also contains a sequence of sediments extending back to before the Ipswichian (Collcutt 1985). The third site, Unnamed Cave no. 2, is less well recorded, but the discovery by Widger of a handaxe of Lower Palaeolithic type in this cave (A.Roberts pers. comm.) suggests that it contains at least some deposits of comparable age to those in Tornewton and Three Holes Caves.

These caves are of considerable importance because of the timespan they cover; few other cave sites in Britain have deposits dating from the period immediately preceding the Ipswichian. In addition Tornewton Cave is unique for the remarkably complete record it provides from the Aveley interglacial to the present.
5.2. Three Holes Cave.

5.2.1. Introduction.

Three Holes Cave consists of a large tubular phreatic passage running for 15 m to where it is blocked by unexcavated sediments (fig. 5.2). At the end the passage widens into a chamber where holes in the roof connect back to the surface, giving the cave its name. A shallow vadose trench is incised in the floor of the passage. The cave lies just south of the Broken Cave, which probably forms the continuation (the latter site has only been partially excavated and has so far yielded material dating back to the Late Devensian).

5.2.2. The Sediments.

When first examined by Widger, the passage was almost choked by sediments leaving a low crawl into the chamber. He excavated extensively, clearing out much of the cave. Three accounts survive and are reproduced by Walker and Sutcliffe (1967). These accounts differ in detail but are sufficiently similar to give a reasonable idea of what Widger found. The basic sequences comprised basal water laid 'river sand' and clays, overlaid by a series of stony sediments variously described as cave earth, rolled stones and Diluvium, interbedded with speleothem floors.
Figure 5.2.

Plan of Three Holes Cave (after Collcutt 1985). The figured sediment sections are shown in fig. 5.3.
Some of these floors were described as fractured and may have comprised broken blocks rather than true floors.

The cave was next excavated by Rosenfeld (1964a). She introduced a system of identifying beds by numbers and recorded different sequences inside and outside the cave. Rosenfeld's stratigraphy is summarised in table 5.1.

Since 1989 the cave has been the site of an annual excavation by a British Museum team directed by A. Roberts. This work is directed mainly at the Upper Palaeolithic and later occupation horizons at the cave entrance but the complete sequence has been reassessed. Combined with sampling carried out by Collcutt (1985) this has resulted in a new interpretation of the sedimentary sequence and its formation, and a new stratigraphic scheme has been established, principally by S.N. Collcutt and A.P. Currant. The author made some contribution to this but worked mainly on the location and analysis of speleothem for dating purposes. The stratigraphy recognised in the 1989 excavation is shown in table 5.1: the distribution of surviving remnants within the cave is shown in figs. 5.2, 5.3. The following sequence is present.

(a) **Rock floor**.

(b) **Hanging Deposits Group**: ancient hard cemented breccias with limestone clasts. They occur as hanging
Figure 5.3.
Sediment sections in Three Holes Cave. Locations of the sections are shown in fig. 5.2.
remnants on the walls at the back of the cave above and overlapped by later deposits.

(c) **Crystalline Wall Speleothems Group**; remnants of a massive crystalline speleothem floor covering the rock floor and draped over the sides of the vadose trench. The floor is extensively fractured and deeply weathered; one block was detached and recemented to the floor before its burial under sediments of the Siliceous Group (S.N.Collcutt pers. comm.). This unit and the foregoing do not occur in contact and their relative ages cannot be ascertained.

(d) **Siliceous Group**; laminated clays with beds and lenses of slate gravel. Fragments of rotted speleothem commonly occur in this unit; at one point a red clay with abundant speleothem occurs, possibly the result of a local collapse (S.N.Collcutt pers. comm.). At the back of the cave the sediments of the Siliceous Group are confined to the vadose trench and the Crystalline Wall Speleothems to either side are directly overlain by sediments of the Calcareous Group.

(e) **Calcareous Group**; further subdivided as follows.

(e.i) **Diamict**; a chaotic deposit of rounded limestone clasts and abundant mineralised bone, matrix supported in dense clay with much small slate (S.N.Collcutt pers. comm.). This unit forms a thin sheet (less than 40 cm
thick) sloping from the back of the cave towards the entrance.

(e.ii) **Conglomerate**; a cave earth composed of a rubbly mass of speleothem and rounded limestone clasts in a hard cemented earthy matrix.

(e.iii) **Speleothem Breccia**; similar to the foregoing but with a much higher proportion of broken speleothem fragments which have coloured the deposit red. These fragments show a strong horizontal preferred orientation (Collcutt 1985). A very dirty thin *in situ* fractured speleothem floor incorporating some clean older blocks occurs near the top of this unit. The Speleothem Breccia and the underlying Conglomerate are seen only at the back of the cave.

(e.iv) **Stony Cave Earth**; angular limestone and some speleothem fragments in a silty matrix. At the back of the cave the deposit is clast supported, being composed mainly of a mass of limestone fragments with a strong preferred orientation dipping to the northwest. Towards the entrance the proportion of limestone clasts is much lower and no preferred orientation can be seen (Collcutt 1985). A charcoal rich band near the entrance appears to be part of a hearth deposit.
(e.v) **Tufa**: soft porous white speleothem forming a floor capping the Stony Cave Earth within the cave and coating walls above this level.

(e.vi) **Stony Talus**: outside the cave entrance the Tufa is absent and the Stony Cave Earth is overlain by a loose talus of angular limestone fragments to boulder size. The boundary between the Stony Cave Earth and the Stony Talus is indistinct and the two deposits grade into each other. Like the Stony Cave Earth the presence of dark bands with flints suggests that hearths are present in this deposit.

The deposits of Three Holes Cave reveal a complex history with at least two periods of sedimentation in subaerial conditions, separated by a period of karst reactivation. Two units, the Hanging Deposits and the Crystalline Wall Speleothem, represent remnants of early sediment fills predating the main Siliceous Group and Calcareous Group sediments. The Hanging Deposits represent an early fill, almost entirely eroded away before the deposition of the Siliceous and Calcareous Groups which buried remnants of the Hanging Deposits left on the walls. Apart from this their relationships with the later sediments cannot be seen and they will not be further discussed here.

The Crystalline Wall Speleothem is likewise an early sediment, and may comprise deposits dating from several periods of speleothem growth. This unit cannot be contemporaneous with the Hanging Deposits because the
Crystalline Wall Speleothem on the floor must have been deposited when the cave was empty. The speleothem floor could predate the Hanging Deposits, but could equally have been deposited after their removal: Collcutt (1985) reported that part of the Crystalline Wall Speleothem overlapped eroded Hanging Deposits, though this does not necessarily mean that all the Crystalline Wall Speleothems postdate the Hanging Deposits. The Crystalline Wall Speleothem is a massive speleothem typical of that deposited in a deep cave environment and is of considerable thickness (up to 30 cm), showing that subaerial conditions prevailed for some time during its formation. Prior to its burial under later sediments the speleothem was fractured, deeply weathered and in places recemented by further speleothem growth. Thus the Crystalline Wall Speleothem shows that the flooding that deposited the Siliceous Group (see below) was preceded by a long period of subaerial conditions, during which a complex series of events took place. The remnants of this early history (the Hanging Deposits and the Crystalline Wall Speleothem) are fragmentary in the extreme, and it is probably impossible to reconstruct the sequence of events that led to their deposition and subsequent disturbance and erosion.

The sediments of the Siliceous Group and the Calcareous Group comprise a more coherent sequence. The gravels and clays of the Siliceous Group show that the deposition of this sequence began with a major change of environment.
The Siliceous group sediments are well bedded with features such as laminated clays and gravel lenses which show that they were deposited by flowing water in a fairly low energy environment with occasional input of gravel during periods of faster flow (Reineck and Singh 1980, Collcutt 1985). At the back of the cave they are confined to the vadose trench suggesting that the Siliceous Group was deposited by a stream flowing in this trench with airspace above. Bones and artefacts (described below) are present in the sediment suggesting that by this time a direct connection with the surface had been opened up, possibly by the same event which caused flooding after the long dry period. The cause of these events is further discussed below.

The Diamict is a very poorly sorted chaotic deposit with a dense fabric, suggesting that it is a debris flow (Fisher 1971, Lawson 1982, Collcutt 1985). The morphology of the deposit also supports this interpretation: it forms a thin sheet sloping down from the chamber and out of the entrance (figs. 5.2, 5.3) suggesting that it flowed from a source somewhere in the back of the cave. Collcutt (1985) has raised the question of why it is preserved on the sides of the vadose trench, but does not fill the trench itself. This has yet to be resolved and is unlikely to be answered without further excavation. A thick deposit may have formed in the trench and have been eroded away later; alternatively the sediment may simply have continued flowing down the passage.
The overlying sediments of the Calcareous Group (the Conglomerate, the Speleothem Breccia and the Stony Cave Earth) are sedimentologically rather similar. Their poor sorting and lack of clearly defined bedding suggests that they are not water laid, but they are sufficiently well bedded to suggest that they were deposited by a process of gradual accumulation. The presence of a hearth in the Stony Cave Earth supports an interpretation of gradual deposition in subaerial conditions, since its presence is irreconcilable with deposition by water or some rapid means such as a debris flow. Thus these sediments fall into the general category of cave earths deposited by a combination of wash, soil creep and collapse processes (Laville 1976, Collcutt et al. 1981, Collcutt 1986).

Several sediment inputs contributed to their deposition. The deposits slope up to, and are thickest at a point directly below the holes in the roof of the chamber suggesting that much of the sediment, including probably the limestone fragments and a wash component represented by the silty matrix, entered here. A different sediment source is represented by fragments of the Hanging Deposits and the Crystalline Wall Speleothem derived from within the cave. The speleothem is abundant in some units; indeed, variations in its abundance is the main feature allowing subdivision of the sequence. These variations in clast lithology must be the result of fluctuations in the relative importance of the various sediment inputs, which might have been due to physical
changes in the cave, or to external climatic fluctuations.

The sediments also show considerable lateral variability. The Conglomerate and Speleothem Breccia are present only in the chamber, suggesting that the speleothem fragments which characterise these units came from a localised source nearby. Towards the entrance the equivalent deposits lack speleothem and have been mapped as the lower part of the Stony Cave Earth.

Collcutt (1985) comments on the lack of structure in these units. He suggests that they might represent old deposits which were left suspended in the cave after sediments beneath were washed out, and that they later collapsed. This seems highly unlikely since it would require their presence as an unsupported and uncemented mass in the upper part of the passage before their subsidence. It seems much more likely that they are in situ; the fine structure could have been disturbed by frost action or compaction processes.

The Tufa within the cave and the Stony Talus outside occupy equivalent stratigraphic positions overlying the Stony Cave Earth. The Stony Talus is a jumbled deposit of limestone blocks (some very large) with interbedded soils, which has clearly accumulated as talus derived from collapse of the adjacent cliff.

<table>
<thead>
<tr>
<th>Layer 1-7</th>
<th>Stony Talus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Stalagmite</td>
<td>Tufa</td>
</tr>
<tr>
<td>Layer 8</td>
<td>Stony Cave Earth</td>
</tr>
<tr>
<td></td>
<td>Speleothem Breccia</td>
</tr>
<tr>
<td></td>
<td>Conglomerate</td>
</tr>
<tr>
<td>Layer 8b</td>
<td>Diamict</td>
</tr>
<tr>
<td>Layer 9</td>
<td>Siliceous Group</td>
</tr>
<tr>
<td>Layer 10</td>
<td></td>
</tr>
<tr>
<td>Cemented Pebble</td>
<td>Hanging Deposits</td>
</tr>
<tr>
<td>Breccia</td>
<td>Group</td>
</tr>
</tbody>
</table>

**TABLE 5.1.**

Correlation of the stratigraphic schemes of Rosenfeld (1964a) and the 1989 British Museum excavations for the sediments of Three Holes Cave.
Comparing Rosenfeld’s stratigraphic scheme with that now recognised, they can be correlated with some confidence (table 5.1). The major difference between the schemes lies in the subdivision of the Diamict and the overlying units, which all look rather similar when seen in the field. Rosenfeld recognised the Diamict as a separate deposit, but mapped it as different units in the cave and talus sequences. She inferred that they are of the same age, but implied that they were derived from different sources and thus distinct (Rosenfeld 1964a). She offered no good evidence for this and this interpretation may be rejected.

5.2.3. Fauna and Archaeology.

All the major workers at Three Holes Cave have provided records of faunal and archaeological material. However, Widger had no scientific training, and in the absence of extant material most of his records must be discarded as potentially unreliable. Hence this account relies mainly upon the work of Rosenfeld (1964a) and Collcutt (1985); the British Museum excavations can be expected to yield considerably greater detail when analysis is complete, but at present details are only available for the highest parts of the sequence. In comparison with many sites Three Holes Cave has yielded only a sparse faunal and archaeological record. Much of the middle part of the sequence is almost barren, and the material recovered
falls into two distinct groups. They are summarised in
Table 5.2 (Rosenfeld 1964a, Collcutt 1985, A.P.Currant
pers. comm., A.Roberts pers.comm.).

The Siliceous Group and the Diamict have yielded similar
sparse faunas dominated by spelaecoid Ursus (cave bear),
suggesting that the cave was a bear den. The associated
species, Crocuta (spotted hyaena), a large felid, small
cervid, bovid and rhino are undiagnostic but the bears
are of considerable interest in that their spelaecoid
characters suggest that they date from before the
Ipswichian Interglacial (A.P.Currant pers. comm.).

A few artefacts are also known from these units. Widger
(Walker and Sutcliffe 1967) recorded finding two flints
in his basal clays and river sands (the Siliceous Group).
One is lost, but the other, a 'steinbort' found in the
Siliceous Group clays, is generally considered to be an
implement still preserved in the Natural History Museum
(Rosenfeld 1964a, Collcutt 1985). This is figured by
Collcutt (1985) and is a triangular handaxe of Upper
Acheulian type. A third flint was found in the Diamict by
Collcutt (1985); this is an unstruck Levallois core.
Collcutt (1985) also describes two flakes and a flint
'chunk' which he considers may have been associated with
the above pieces either in situ or derived in later
sediments. The Acheulian handaxe and the Levallois core
are of particular interest in that they represent tool
types typical of the late Lower Palaeolithic (Wymer
<table>
<thead>
<tr>
<th>Species</th>
<th>Stony Cave Earth</th>
<th>Diamict</th>
<th>Siliceous Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homo sapiens</td>
<td>?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Canis lupus</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ursus sp.</td>
<td>X X X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crocuta crocuta</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Felid</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Equus ferus</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rhinoceros</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cervus elaphus</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rangifer tarandus</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cervid</td>
<td>X X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bovid</td>
<td>X X</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TABLE 5.2. Fauna of Three Holes Cave, from Rosenfeld 1964a, Collcutt 1985, A.P. Currant, A. Roberts pers. comm.).
1986). They could well be more or less contemporaneous and would not be out of place in the Middle Pleistocene context suggested by the bears. This suggests that the fauna and artefacts may form a coherent assemblage. Considering the sedimentary environment this assemblage is clearly not in situ but there is no reason to suppose that it much predates the sediments.

Above the Diamict, much of the Calcareous Group is almost barren: Rosenfeld (1964a) records that sieve samples from these sediments yielded neither rodents nor molluscs. The hearths near and at the top of the Stony Cave Earth have yielded a flint industry with associated fauna (Rosenfeld 1964a, Collcutt 1965, A.Roberts pers. comm.). The flints are of Late Upper Palaeolithic type, suggesting that this part of the sequence dates from the Devensian Late Glacial. The fauna is dominated by Equus (horse) but also includes Cervus elaphus (red deer), Ursus (bear) and possibly Rangifer (reindeer) and Homo (man) from the hearths, and Canis lupus (wolf), Crocuta and Rangifer from the underlying sediments. None of these would contradict the age implied by the flint industry.

Above the Stony Cave Earth the Tufa is barren, but its position stratigraphically above the Late Upper Palaeolithic implies that it is Holocene in age. Outside the cave the Stony Talus has yielded Mesolithic and Neolithic industries with associated faunas which unequivocally show it to be Holocene, and thus outside
5.2.4. Age of the deposits.

Speleothems were sampled for uranium series analysis by the author during the 1989 excavation season. All the samples were detritally contaminated. The thin floor at the top of the Speleothem Breccia was found to be too dirty to be worth analysis: the ages of the remaining samples were corrected for detrital contamination using method 1 (equation 8) of Schwarcz (1980). Some of the samples were also porous, suggesting that they may have been affected by leaching. Three detached blocks of Crystalline Wall Speleothem in the sediments at the back of the cave were analysed. The stratigraphic positions of the samples and the ages obtained are shown in fig 5.4: details of the analyses are given in table 5.3.

THC-89-3B was a large block of flowstone floor draped over the side of the vadose trench and buried by clays of the Siliceous Group. The block was detached from the wall but probably not far from growth position. This yielded an age of 319 (258-462) ka, providing a maximum age for the Siliceous Group and also for the disruption that broke up the floor. THC-89-4, a broken stalactite, was buried in Siliceous Group clays close to THC-89-3B, and had clearly fallen there from a growth site on the roof.
Figure 5.4.
Schematic section of deposits at the back of Three Holes Cave showing the locations of dated speleothems. Preliminary TL ages are from N. Debenham (pers. comm.). Ages are in ka.
<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Name</th>
<th>Yield U%</th>
<th>Th%</th>
<th>U μg/g</th>
<th>234U</th>
<th>230Th U</th>
<th>232Th</th>
<th>Age (ka) Uncorrected</th>
<th>Age (ka) Corrected</th>
</tr>
</thead>
<tbody>
<tr>
<td>6672</td>
<td>THC-89-4B</td>
<td>59</td>
<td>18</td>
<td>0.054</td>
<td>1.095±0.011</td>
<td>0.899±0.022</td>
<td>17.5±1.1</td>
<td>229 (211-252)</td>
<td>224 (206-247)</td>
</tr>
<tr>
<td>6713</td>
<td>THC-89-4C</td>
<td>70</td>
<td>25</td>
<td>0.074</td>
<td>1.146±0.014</td>
<td>0.963±0.022</td>
<td>10.5±0.5</td>
<td>286 (257-325)</td>
<td>277 (247-317)</td>
</tr>
<tr>
<td>6715</td>
<td>THC-89-5B</td>
<td>40</td>
<td>4</td>
<td>0.048</td>
<td>1.188±0.019</td>
<td>0.956±0.049</td>
<td>2.56±0.18</td>
<td>267 (221-345)</td>
<td>224 (176-306)</td>
</tr>
<tr>
<td>6759</td>
<td>THC-89-3B</td>
<td>52</td>
<td>17</td>
<td>0.041</td>
<td>1.123±0.024</td>
<td>0.984±0.036</td>
<td>11.8±1.1</td>
<td>327 (267-469)</td>
<td>319 (258-462)</td>
</tr>
</tbody>
</table>

**TABLE 5.3.**

Uranium series analyses from Three Holes Cave.
or wall. Two samples from this speleothem were analysed. THC-89-4B, from the middle of the stalactite, yielded an age of 224 (206-247) ka; THC-89-4C, from the outer layers, yielded an age of 277 (247-317) ka. These ages are stratigraphically reversed; THC-89-4B is probably more reliable since THC-89-4C was porous and nearer the outside surface of the stalactite, and thus likely to have been affected by leaching. This stalactite, like THC-89-4B, provides a maximum age for the Siliceous Group and provides considerably greater constraint than the latter sample. The last speleothem analysed, THC-89-5B, was a detrital block of flowstone from the Stony Cave Earth. This yielded an age of 224 (176-306) ka, giving a maximum age for the Stony Cave Earth. In summary, the presence of detrital blocks of Crystalline Wall Speleothems dating from around 319 to 224 ka (and particularly the presence of THC-89-4B dating from around 224 ka near the base of the sequence) suggests that the Siliceous and Calcareous Group sediments were deposited after around 224 ka. The ages also suggest that the Crystalline Wall Speleothems are not all of equivalent age.

Speleothems from the cave are also being dated by N. Debenham using thermoluminescence methods. This work is still in progress but preliminary results have been obtained for two samples (N. Debenham pers. comm.). THC-89-4 yielded a preliminary age of 159 (130-188) ka. This is somewhat younger than the equivalent U-series age but
overlaps at two standard deviations. THC-1, a sample from the dirty floor at the top of the Speleothem Breccia has yielded a preliminary age of 130 (102-158) ka. This sample is important since it provides an age for a point halfway up the sequence. Clearly both results are potentially of considerable interest; however detailed discussion should await production of finalised results.

Comparison with the oxygen isotope record (Imbrie et al. 1984) suggests that the Siliceous Group and Calcareous Group were deposited during oxygen isotope stage 7 or later. The fauna and artefacts are unlikely to be earlier since the growth of massive speleothems before this time suggests the cave was sealed. The spelaeoid bears and Lower Palaeolithic implements suggest the lower part of the sequence, the Siliceous Group and the Diamict, predate the Ipswichian Interglacial, dated to isotope stage 5e (125 ka) at Victoria Cave (Gascoyne et al. 1981); this is given considerable support by Debenham's preliminary age of around 130 ka for the speleothem at the top of the Speleothem Breccia. Thus this assemblage can be dated to isotope stage 6 or 7.

The top of the Stony Cave Earth is known to date from the Devensian Late Glacial (the end of isotope stage 2) so the attribution of the base of the sequence to isotope stage 7 or 6 implies that either deposition was very slow or that there are hiatuses in the sequence. Both are probably true. The cave's position at the edge of the
plateau above means that once flooding had ended sediment sources were restricted to a slow accumulation of material from this plateau, with additional minor aeolian and authigenic inputs. In addition the presence of speleothem floors in the sequence suggests that at times the input of allochthonous sediments virtually (or entirely) ceased. S.N. Collcutt and A.P. Currant (pers. comm.) have suggested that this may have occurred during warm periods when vegetation cover prevented sediment transport: the Tufa is almost certainly Holocene and Debenham’s age for the speleothem in the Speleothem Breccia, which suggests a correlation with the Ipswichian Interglacial, also supports this hypothesis.

Of particular interest to the karst history of the Torbryan valley is the evidence in Three Holes Cave for a period of karst reactivation and flooding during oxygen isotope stage 7 or 6. This is of considerable significance in the interpretation of Tornewton Cave (described below).

5.3. Tornewton Cave.

5.3.1. Introduction.

Tornewton Cave is situated 200 m downvalley from Three Holes Cave, and is the largest in a small group of caves that also includes the Old Grotto and Unnamed Cave no. 2.
Tornewton Cave itself is complex in form, with three entrances (fig. 5.5). The Main Chamber of the cave comprises a vertical rift some 12 m high with an entrance at the top (the Upper Entrance) and passages leading off at either end (Rolfe's Rift and the Lower Tunnel). The Lower Tunnel connects to the Lower Entrance. Holes halfway up the northwest wall of the Main Chamber connect to two passages parallel to it, Vivian's Vault and the Middle Tunnel connecting to the Middle Entrance.

When first examined by Widger (Walker and Sutcliffe 1967) only the Upper Entrance and the topmost part of the Main Chamber were open. He made his first finds of Pleistocene fauna here, and went on to excavate to a depth of several m, discovering rich faunal remains and opening up the Middle Tunnel, Vivian's Vault and a fourth side passage (Widger's Tunnel no.1) which has never since been satisfactorily identified. Widger's brief account of the cave sediments was published in the Torquay Directory of 1892: full details are reproduced by Walker and Sutcliffe (1967). Between 1936 and 1939 the cave was excavated by A.H. Ogilvie of the Torquay Natural History Society (Sutcliffe and Zeuner 1962). Their standard of excavation appears to have been abysmal and no accounts or even notebooks from this work are known to survive (P. Berridge pers. comm.) although a considerable quantity of unprovenanced finds reside in Torquay Museum.
Figure 5.5.
Survey of Tornewton Cave.

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A third excavation was carried out by Sutcliffe and Zeuner between 1944 and 1969 (Sutcliffe 1957, Sutcliffe and Zeuner 1962, Harrison 1980). Sutcliffe and Zeuner (1962) established the stratigraphy now in use at the site and described a sequence of climatic variations recorded as changes in the mammalian faunas. They described an early cold fauna overlain by an Ipswichian Hippopotamus fauna, which was in turn overlain by a typical Devensian cold fauna. Collcutt (1985) examined the cave and took sediment samples. He pointed out discrepancies between Widger's and Sutcliffe's accounts and questioned many of Sutcliffe's conclusions, most importantly the interpretation of a void within the sediments and the existence of Sutcliffe's cold-warm-cold faunal sequence.

The author started work at the site in 1989 in an attempt to sort out some of the stratigraphic problems and locate speleothem suitable for dating. This work went some way to achieving these aims; in particular by the recognition of ancient speleothem wall remnants which had confused both Sutcliffe and Collcutt, and some ages were obtained for the sequence. In 1990 the British Museum excavation was expanded to cover Tornewton Cave and A.P. Currant started work at the site. The author continued mapping and dating work in 1990 and 1991; a final excavation season was carried out by A.P. Currant in 1992. The reinterpretation of the cave has been greatly facilitated.
by A.J. Sutcliffe who has provided on site discussion and made available unpublished diaries and sections.

5.3.2. The sediments.

The sedimentary sequence in Tornewton Cave is far from simple, reflecting the complex nature of the cave and the multiple sediment sources provided by the various entrances. Sutcliffe (1957) and Sutcliffe and Zeuner (1962) described two separate sequences; the talus outside, and the cave earths within the cave (fig. 5.6). These were only connected by narrow sediment bodies extending through the Middle and Lower Tunnels, both of which were extensively disturbed by excavation before the sediments were recorded. Thus it is difficult to properly correlate the two sequences and they are described separately below.

The Talus was a wedge shaped deposit filling the gully leading to the Middle and Lower Entrances. Widger cut a trench into the Talus to gain access to the Middle Entrance, but left the bulk of the deposits in place (Walker and Sutcliffe 1967). Sutcliffe and Zeuner (1962) excavated much more extensively, and removed the entire sediment body with the exception of a few small patches on alcoves and ledges. These are now rapidly collapsing and it is difficult to determine which material is in situ. The account below is thus a summary of those in
Sutcliffe (1957) and Sutcliffe and Zeuner (1962). Collcutt (1985) gives a detailed account of the surviving sediment remnants. The sequence was as follows (fig 5.6).

(a) **Contorted laminated clay**: a much deformed deposit of finely laminated clay with occasional coarser layers, exposed by excavation in the Lower Entrance and not bottomed. At the outer edge of the Talus a (contemporaneous?) red clay with speleothem fragments was found.

(b) **Head**: divided into 4 facies, interbedded in a complex fashion.

(b.i) **Quartz pebble facies**: numerous rounded pebbles of vein quartz and local igneous rocks in earthy matrix with abundant slate fragments.

(b.ii) **Slaty/Loamy facies**: rounded cleavage fragments of slate with a little clay. Sutcliffe and Zeuner suggested that this and the foregoing represent the reworked remains of an alluvial deposit.

(b.iii) **Stalagmite block facies**: occasional fragments of speleothem and limestone in an earthy matrix, with much small slate.

(b.iv) **Limestone rubble facies**: abundant small fragments of limestone in an earthy matrix.
Figure 5.6.
Sutcliffe and Zeuner's (1962) longitudinal section of Tornewton Cave.
(c) Elk Stratum; a thin fossiliferous horizon at the top of the Head, and sedimentologically similar to it. Sutcliffe and Zeuner suggest it represents mixing of bone into the top of the Head, with little or no contemporaneous accumulation of clastic sediment.

(d) Grey Loam; a localised earthy deposit occurring just outside the Middle Entrance, containing a great abundance of small fragments of slate.

(e) External Reindeer Stratum; an almost stoneless red earth with abundant antler and bone.

(f) Eboulis; a thick loosely packed deposit of angular limestone blocks, forming a wedge shaped deposit thickest at the cliff base and thinning out some 12 metres from it.

(g) Old soil; dark humus rich rendzina, probably actively forming before burial by tip.

(h) Tip; from Widger’s and Ogilvie’s excavations.

The Contorted laminated clay is clearly a water laid sediment deposited in low energy conditions (Reineck and Singh (1980), Collcutt (1985). Sutcliffe and Zeuner (1962) suggested that the Head is a solifluction deposit. They attributed the Reindeer Stratum and Eboulis to wash
of material from the plateau above, and collapse respectively. Collcutt (1985) reached broadly similar conclusions, and further suggested that the fine component of the Head might be loessic in origin. The deposits of the external sequence were never satisfactorily correlated with the internal sediments. They are thus of little use in attempting to date the sequence and will not be further discussed here.

A large part of the Main Chamber sequence was excavated by Widger who left a brief account of the stratigraphy. Ogilvie also did his worst in this part of the cave and by the time Sutcliffe started work the upper layers had been completely destroyed. He attempted to reconstruct them from wall remnants of speleothems, which he correlated with those described by Widger. The scheme so produced disagreed with Widger's on bed thicknesses, a problem largely ignored by Sutcliffe (1957) and Sutcliffe and Zeuner (1962). Mapping by the author in 1990 showed that many of the wall speleothems are ancient remnants, with drapes of later speleothem and cemented sediment over old break faces, showing that they had broken before the accumulation of the present fill and were unrelated to the sequence recorded by Widger. One floor remnant (beside the entrance to Vivian's Vault at the back of the Main Chamber), had stalactite columns extending down from its base, showing the sediment on which it had grown had been eroded away from beneath and the columns had formed, before its burial by the present fill. Remapping of the
### TABLE 5.4.

Comparison of bed thicknesses for the upper deposits of Tornewton Cave, according to the schemes of Widger (Walker and Sutcliffe 1967), Sutcliffe and Zeuner (1962), and the author and A.P. Currant (this thesis).

<table>
<thead>
<tr>
<th>Unit</th>
<th>Widger</th>
<th>Sutcliffe and Zeuner</th>
<th>Proctor and Currant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diluvium</td>
<td>1.5 m</td>
<td>1.5 m</td>
<td>1.3 m</td>
</tr>
<tr>
<td>Stalagmite Floor</td>
<td>0.1 m?</td>
<td>0.2 m</td>
<td>0.2 m</td>
</tr>
<tr>
<td>Reindeer Stratum</td>
<td>1.8 m</td>
<td>0.8 m</td>
<td>1.9 m</td>
</tr>
<tr>
<td>Dark Earth</td>
<td>0.6 m</td>
<td>0.7 m</td>
<td>0.6 m</td>
</tr>
<tr>
<td>Hyaena Stratum</td>
<td>0.9 m</td>
<td>0.9 m</td>
<td>1.0 m</td>
</tr>
</tbody>
</table>
upper part of the chamber using sediment remnants showed Sutcliffe's interpretation to have been substantially in error. In particular, a speleothem remnant at the inner end of the Middle Tunnel, which was taken by Sutcliffe to mark the top of the Reindeer Stratum, is an ancient remnant (see the Middle Tunnel, below). Remnants of Reindeer Stratum have been mapped by the author and A.P. Currant up to the level of a tufaceous floor which can be traced all round the walls of the Main Chamber (fig. 5.7), and lies a metre higher than Sutcliffe's remnant. A new reconstruction using this floor to mark the top of the Reindeer Stratum agrees much more closely with the bed thicknesses given by Widger (Walker and Sutcliffe 1967), (table 5.4). Work on the sediments of the Main Chamber is being continued by A.P. Currant, who has found wall remnants of sediment predating the present fill, in addition to the speleothems.

Taking the above revisions into account, the following sequence is present in the Main Chamber and the Lower and Middle Tunnels. The distribution of the sediment units is shown in figs. 5.7, 5.8, 5.9.

(a) Ancient Wall Speleothems; remnants of crystalline speleothem floors and bosses cemented to the walls. In the Lower Tunnel remnants of two floors of different ages are present, with the later floor cutting across the broken remnant of the earlier floor; this suggests that
Figure 5.7.

Longitudinal section of the Main Chamber and Lower Tunnel, Tornewton Cave, based on Sutcliffe (1957, unpublished sections) and mapping by the author.
Figure 5.8.

Longitudinal section of Vivian's Vault and the Middle Tunnel, Tornewton Cave, based on Sutcliffe (1957, unpublished sections) and mapping by the author.
at least two distinct phases of speleothem growth occurred on different fills.

(b) Ancient Sediment Remnants; patches of very hard cemented sediment on the walls, comprising a chaotic mixture of abundant fragments of slate (and some quartz) to around 2 cm, clast to matrix supported in an earthy matrix. At the inner end of the Middle Tunnel a patch lies beneath ancient speleothem but it is unclear whether it is the sediment on which the speleothem grew: there is a small gap between them. These ancient sediment remnants are dissimilar to the main bulk of the sediments above the Glutton Stratum and apparently represent the remains of an early fill (A.P. Currant pers. comm.).

(c) Laminated Clay; finely bedded clay and silt, with rare fine sand lenses (Collcutt 1985). The bedding is draped down the walls and the deposit extends 1.5 metres higher up the walls than at the centre of the rift (fig. 5.9). The surface of these wall drapes were slickensided where they were in contact with the Glutton Stratum (A.J. Sutcliffe pers. comm.), and faulting and deformation are visible within the sediment (Collcutt 1985), showing that it has slumped downwards after its deposition. The present floor of the Main Chamber and Lower Tunnel comprise Laminated Clay, though there are few clean sections where the deposit can be examined.
(d) **Glutton Stratum**: a chaotic deposit with many large clasts of limestone and speleothem to about 40 cm in size, set at all angles in a matrix of very dense clayey silt with abundant small slate clasts (to gravel size): yellowish red in colour (Collcutt 1985). Bone is very common. A standing section of Glutton Stratum remains in the pit at the inner end of the Main Chamber, and there are wall remnants in the Main Chamber. It also fills pipes descending into the underlying Laminated Clay, some of which remain unexcavated (A.J. Sutcliffe pers. comm.).

(e) **Silt Lens**: a sediment body shown on Sutcliffe’s sections at the inner end of the Lower Tunnel was a lens of silty sediment (A.J. Sutcliffe pers. comm.). It was destroyed by excavation and no remnants have been identified.

(f) **Bear Stratum**: yellowish red clayey silt with limestone, speleothem and slate clasts to around 6 cm, and many bone fragments. The Bear Stratum was almost completely removed by Sutcliffe, who left only small remnants on the walls of the Main Chamber. These show an apparently chaotic fabric, but they may not be representative of the deposit as a whole because they lie so close to the walls (Collcutt 1985). Sutcliffe and Zeuner (1962) noted that the uncemented parts of the deposit were much less compact than the Glutton Stratum and that it contained fewer large clasts, mostly
limestone. They also recorded signs of faint stratification and articulated bone groups in this unit.

(g) **Hyaena Stratum**; a chaotic deposit of clayey silt with some clasts of speleothem and slate. The colour is very variable, sometimes yellowish but often heavily speckled (Collcutt 1985). Bone and coprolites are extremely abundant, and Sutcliffe and Zeuner (1962) recorded the occurrence of associated groups of small bones, and a bed composed of coprolitic material in the upper part of the deposit. The Hyaena Stratum was mostly removed by Sutcliffe, but there is a sizeable remnant in the roof at the inner end of the Lower Tunnel, and smaller remnants on the walls of the Lower Tunnel and Main Chamber.

(h) **Stalagmite Floor**; recorded by Sutcliffe and Zeuner (1962) as 'an inch thick', and much shattered. No remnants of this speleothem floor could be found in 1991 when the cave was examined by Sutcliffe and the author, although a few fragments could be seen at the outer end of the Main Chamber until quite recently, when they were sampled by Sutcliffe and H.P. Schwarcz (A.J. Sutcliffe pers. comm.)

(i) **Dark Earth**; uncremented dark yellowish grey earth, still visible capping the Hyaena Stratum in the roof of the Inner Tunnel.
(j) **Reindeer Stratum**: yellowish red clayey silt with bone, some limestone clasts and many small slate fragments: the larger clasts show subhorizontal orientation (Collicutt 1985). The Reindeer Stratum is preserved within the Main Chamber as cemented remnants on the walls and pockets within alcoves. The lower part of the sediment section remaining in the Middle Tunnel is probably referrable to this unit (see below).

(k) **White Stalagmite Floor**: a soft tufaceous speleothem floor 10-20 centimetres thick, preserved as wall remnants in the Main Chamber.

(l) **Diluvium**: pale brown clayey silt with scattered small slate fragments and bone fragments and abundant snail shells. Where it is uncemented, the Diluvium is loose and unconsolidated, with a vuggy pelleted texture. The Diluvium occurs as small cemented remnants in the Main Chamber above the White Stalagmite Floor (k), and forming the upper part of the deposits in the Middle Tunnel.

(m) **White Stalagmite Floor**: 'about one foot thick' (Walker and Sutcliffe 1967). Possible remnants of a tufaceous speleothem floor remaining high on the chamber walls might be referrable to this unit.

(n) **Black Mould**: totally excavated by Widger (Walker and Sutcliffe 1967); probably a recent soil.
Slabs of Angular Stones; removed by Widger (Walker and Sutcliffe 1967).

Within the Main Chamber the full sequence is present (figs. 5.7, 5.9). A horizontal void cut across the gently dipping Hyaena Stratum and Bear Stratum in this chamber. The void connected at its outer end with the airspace in the upper part of the Lower Tunnel (see below).

The Lower and Middle Tunnels show partial sequences (figs. 5.7, 5.8, 5.9) which can nonetheless be clearly related to that of the Main Chamber. The Lower Tunnel shows a complete sequence up to the Hyaena Stratum, which appears to have blocked both ends of the Lower Tunnel when originally deposited. Above it was an airspace, and in places speleothem bosses (destroyed by Sutcliffe's excavations). On top of the bridge at the outer end of this passage was a very localised deposit rich in rodent bones, the 'Rodent Deposit' (Sutcliffe 1957). This deposit and the surrounding sediments were destroyed by excavation and blasting to open the Lower Entrance, before they were properly recorded. Thus the stratigraphy here, and the relationships of the Rodent Deposit to the sediments further inside the cave were never satisfactorily determined (A.J. Sutcliffe, S.N. Collcutt pers. comm.).

The Middle Tunnel is somewhat more problematical. Widger (Walker and Sutcliffe 1967), Sutcliffe (1957) and
Sutcliffe and Zeuner (1962) describe it as being filled with Diluvium, although Sutcliffe (1957) did propose that a layer of Reindeer Stratum might have occupied the lower part of the passage. The bulk of the sediment here is similar to the Reindeer Stratum of the Main Chamber, and this is confirmed by the palaeontology of the deposit (see below). The uppermost sediments comprise snail earth referrable to the Diluvium and it seems probable that the stratigraphy of the Middle Tunnel was Reindeer Stratum with a thinner layer of Diluvium above (fig. 5.8). The remnants of the two deposits can be seen to be separated by thin impersistent speleothem floors. At the inner end of the Middle Tunnel a massive crystalline floor is that used by Sutcliffe to suggest the height of the top of the Reindeer Stratum. However it has ancient break faces recemented by a newer layer of speleothem which was in its turn buried under Reindeer Stratum: there is no doubt that the floor is an ancient remnant. This speleothem has a small remnant of slate rich sediment adhering to its base, almost certainly also an ancient remnant.

The small chamber leading off from halfway up the back wall of the Main Chamber, Vivian’s Vault, has a stratigraphy differing very significantly from the Main Chamber and deserving of detailed description. Widger recorded a sequence of Bear Stratum, Bone Bed (=Hyaena Stratum), and at the top, fine red earth. Sutcliffe found a unique deposit, the Otter Stratum (Sutcliffe and Kowalski 1976) which he found nowhere else in the cave.
Because the upper part of the Vivian's Vault sequence had been removed by earlier excavations he was unable to relate this deposit to Widger's description, or to the Main Chamber sequence. This was achieved in 1990 by A.P. Currant, who found that a set of steps down into the chamber were cut into a tiny remnant of intact sediment which extended right up to the lip of the entrance hole. This preserved remnants of Bear Stratum and Hyaena Stratum overlying the Otter Stratum, and allowed the reconstruction of the sequence to around a metre higher than previously thought possible. The author subsequently located parts of the same sequence preserved in remnants at the other end of Vivian's Vault, allowing a tentative reconstruction of the stratigraphy of the entire chamber (figs. 5.8, 5.9). The sequence is as follows.

(a) **Ancient Wall Speleothem;** at the end of Vivian's Vault a massive speleothem boss has broken faces buried by Hyaena Stratum, suggesting that it predates the present fill.

(b) **Laminated Clay;** recorded by Sutcliffe (unpublished section) although not reported in his published descriptions (Sutcliffe 1957, Sutcliffe and Zeuner 1962). Laminated Clay was again exposed by A.P. Currant during sampling of the Otter Stratum. It has not been bottomed.

(c) **Otter Stratum;** red clay/silt with abundant broken blocks of speleothem, fine slate fragments and much
broken and stained bone. Some of the speleothem blocks have bone embedded in them. This unit is chaotic with speleothem blocks in all orientations. Clast supported in places. The Otter Stratum forms the present floor of Vivian's Vault. The topmost layers are loose (perhaps due to disturbance by previous excavation), but it is much more compact at depth.

(d) Bear Stratum; hard cemented clay/silt with some slate fragments and abundant stained bone, preserved in the wall section at the entrance to Vivian's Vault.

(e) Hyaena Stratum; yellowish hard cemented clay/silt with very abundant unstained bone. Wall remnants of Hyaena Stratum occur in the section at the entrance to Vivian's Vault, and beside the ancient speleothem boss at the far end.

(f) Red Earth; recorded by Widger (Walker and Sutcliffe 1967) but not positively located recently.

At the end of the Main Chamber a hole at floor level drops into another passage, Rolfe's Chamber (figs. 5.7, 5.9). At the entrance a deep sounding by Sutcliffe and Zeuner (1962) revealed Glutton Stratum filling a pipe in Laminated Clay. Further in the chamber has not been excavated, but has a 2 metre high void over a floor comprising limestone and speleothem boulders in a clay matrix. The clay might be of recent origin: the chamber
regularly floods in wet weather. Rolfe's Chamber might be Widger's Tunnel no.1, which he described as '20 feet long... the entrance to the rocky floor of the cave... with the exception of the original crust lying at the bottom, [it] was empty.' (Walker and Sutcliffe 1967). Against this it should be noted that A.J. Sutcliffe (pers. comm.) believes the deposits he removed to enter Rolfe's Chamber around 1960 were in situ, although it is possible that the frequent flooding of this part of the cave may have compacted spoil and obliterated any obvious signs of previous visitors. Thus while Rolfe's Chamber might be Widger's Tunnel no.1, at present this remains unproven.

The Laminated Clay has the characteristic features of a sediment deposited in water in low energy conditions (Reineck and Singh 1980, Collcutt 1985) and indicates that a period of flooding preceded the deposition of the bone deposits. The presence of ancient speleothem remnants on the walls suggests that before the deposition of the Laminated Clay the cave was filled with sediment and speleothem which was subsequently removed, perhaps by the flood which deposited the Laminated Clay. Multiple speleothem floors in the Lower Tunnel show that several fills accumulated and were removed before the deposition of the present sediments, suggesting that this sequence of events may have been repeated several times.

The very poor sorting, dense matrix, lack of internal structure and chaotic clast orientation in the Glutton
Stratum suggest that it was emplaced as a debris flow (Fisher 1971, Lawson 1982, Collcutt 1985). This conclusion is supported by the Glutton Stratum's morphology and relationships to the underlying Laminated Clay, which show that it has slumped downwards by at least 1.5 metres and has descended down pipes into the latter deposit. Furthermore some of the ancient sediment remnants high on the walls of the Main Chamber (one 3 metres above the present top of the Glutton Stratum) closely resemble Glutton Stratum and hint at a much greater amount of movement. The evidence for repeated flooding discussed above provides a possible mechanism for the emplacement of the Glutton Stratum into its present position. It is clear that some mechanism has simultaneously removed sediment from the base of the sequence, causing extensive collapse, and caused waterlogging, resulting in the formation of pipes in the Laminated Clay and flow of the Glutton Stratum into its present position. The most likely cause is a minor flood that removed the lower part of the Laminated Clay (possibly by piping resulting from water flowing along the base of the Main Chamber) and saturated the sediments, leading to their liquefaction and collapse. This event has clearly not affected deposits higher than the Glutton Stratum, and thus must have occurred between the deposition of the Glutton Stratum and the Bear Stratum.
The position of the Otter Stratum in Vivian's Vault is a little problematic. It occupies a similar stratigraphic position to the Glutton Stratum, between Laminated Clay and the Bear Stratum. Like the Glutton Stratum, it is a poorly sorted, structureless, chaotic deposit suggesting a similar depositional history. However it has features not found in the Glutton Stratum, notably certain unique faunal elements (see below) and broken blocks of a dirty speleothem floor containing embedded fauna. These features serve to demonstrate that the Otter Stratum is not a direct correlative of the Glutton Stratum; nevertheless its morphology and stratigraphic position suggest a genetic relationship with the latter deposit.

The Bear Stratum, Hyaena Stratum, Reindeer Stratum and Diluvium are less compacted than the underlying Glutton Stratum. They have features such as poor sorting, and large scale bedding structure but a lack of clear stratification on a small scale, which are characteristic of subaerial cave earths formed by a combination of wash, soil creep and collapse processes (Laville 1976, Collcutt et al. 1981, Collcutt 1985, 1986). This is supported by the very abundant fauna, with features such as articulated bone groups and coprolites which are consistent with a process of gradual accumulation of sediment in subaerial conditions with animals living and dying within the cave.
The Bear Stratum and the Hyaena Stratum are characterised by the huge abundance of bone within them. Sutcliffe and Zeuner (1962) record that tens of thousands of bones and teeth were excavated from the Hyaena Stratum alone, and the Bear Stratum appears to have been scarcely less rich. Remnants of these deposits in the cave can be seen to contain large quantities of bone, in places forming a true 'bone breccia' (in which bone forms the bulk of the large particles). The species involved (hyaenas and bears; see below) suggest that they accumulated as a result of denning activity. The animals must have entered the cave through the Lower and Middle Entrances. Such a massive accumulation of bone must represent deposition over a considerable period, and the sedimentation rate must have been correspondingly slow. The fine fraction probably represents material washed in from the plateau above through roof fissures or the Top Entrance. The inferred low sedimentation rate suggests the latter must have been more restricted than today (or perhaps completely blocked). A collapse component is represented by limestone and speleothem clasts, probably derived from the cave walls and roof and (if the Top Entrance was open) the cliff outside. Some sediment may also have been brought in by animals. The Otter and Glutton Strata also contain huge quantities of bone and many of the above conclusions can probably also be applied to those deposits, though their disruption has obliterated many of the features (such as coprolites and articulated bone groups) seen in the Bear and Hyaena Strata.
The Reindeer Stratum and Diluvium must have been deposited in large part at least, by the accumulation of material washed in through the top entrance, which lies above the thickest parts of these units in the Main Chamber, and is also the only entrance high enough to have acted as a source of sediment for at least the Main Chamber part of these deposits. The small amount of limestone in these sediments suggests collapse processes were not very important during their accumulation.

The void halfway up the deposits of the Main Chamber (fig. 5.7) has been much discussed by previous workers. Sutcliffe (1957) suggested that the Main Chamber sequence is basically in situ, and that the void has opened up due to compaction of the lower sediments, which left the cemented upper deposits hanging above a shallow cavity. Collcutt (1985) argued for a different origin and suggested that the lower part of the deposits had been completely washed out, the large cavity thus produced being filled by Devensian sediments represented by the Glutton and Bear Strata. This interpretation, if true, would destroy the integrity of the stratified faunal sequence in the cave (see below). Insufficient sediment remnants remain in the cave to address this argument. However, it is disproved by Sutcliffe's (1957, pers. comm.) sections of the cave and field notes. Unlike the section published by Sutcliffe and Zeuner (1962), Sutcliffe's earlier sections make a clear distinction
between observed stratigraphy and speculative reconstruction. They unequivocally show that the Bear Stratum occurred stratified below the Hyaena Stratum in sediment blocks bridging the roof of the void, a position it could not occupy if it postdated the void. Thus the Bear Stratum (and the underlying Glutton Stratum) must predate both the Hyaena Stratum and the void, providing strong evidence that the sequence is in situ and that Sutcliffe's interpretation was correct. The presence of the void thus implies that downward movement of the lower part of the Hyaena and Bear Strata has occurred. This might perhaps have been due to minor late stage collapse of the Laminated Clays and Glutton Stratum beneath them. The small amount of downward movement involved (less than 0.5 m) would probably not have seriously disrupted the Bear and Hyaena Strata, which is consistent with the relatively undisturbed state of the deposits reported by Sutcliffe and Zeuner (1962).

5.3.3. Fauna and Archaeology.

In contrast to Three Holes Cave, very rich faunal remains have been found in most of the Tornewton Cave sequence. The early excavators, Widger and Ogilvie, left few or no records of their finds (Sutcliffe 1957, Walker and Sutcliffe 1967) but they left large volumes of most of the fossiliferous units and detailed faunal lists are provided by Sutcliffe (1957), Sutcliffe and Zeuner.
(1962), Sutcliffe and Kowalski (1976) and Harrison (1980). Sutcliffe (1957) described the sequence for which the cave has become famous, with a basal 'Wolstonian' cold stage fauna, overlain by warm and cold stage faunas attributed to the Ipswichian and Devensian respectively. The fauna is currently being reassessed by A.P.Currant and L.Cornish, both by examination of previously excavated material in the BM(NH) and by excavation of sediment remnants in the cave. This work is of considerable importance and has already necessitated substantial revisions to the published faunal lists.

A preliminary faunal list incorporating some of the new work of A.P.Currant and L.Cornish (pers. comm.) is given in table 5.5. It must be stressed that the list reproduced here has been assembled by the author from early results provided by Currant and Cornish: any errors are the author's responsibility. Work is continuing and a proper account will be produced by Currant and Cornish in due course.

This faunal list incorporates major alterations to those previously published by Sutcliffe (1957), Sutcliffe and Zeuner (1962) and Sutcliffe and Kowalski (1976). The most important is the position of Hippopotamus amphibius (hippo). This species was reported to have come from the Hyaena Stratum but labelled specimens in the BM(NH) (A.P.Currant pers. comm.) and the unpublished excavation diaries of A.J.Sutcliffe show that a large amount of
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<td></td>
</tr>
<tr>
<td>Sus scrofa</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Megaloceros giganteus</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Dama dama</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Cervus elaphus</td>
<td>X</td>
<td>?</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rangifer tarandus</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
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<tr>
<td>Bos/Bison sp.</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bird</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frog/toad</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fish</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TABLE 5.5. Fauna of Tornewton Cave, from Sutcliffe and Zeuner (1962), and A.P. Current, L. Cornish pers. comm.
Hippopotamus material was in fact found in the underlying Bear Stratum. Furthermore, in the diaries there is no reference to Hippopotamus ever having been found in the Hyaena Stratum. Here another problem presents itself, for early in the excavation Sutcliffe and Zeuner did not recognise the Bear and Glutton Strata as separate units, potentially leading to further confusion regarding the origin of the Hippopotamus remains. However, Sutcliffe’s diaries record that Hippopotamus was found early in the excavations in blocks of sediment which by comparison with published elevations of the cave (Sutcliffe 1957, Sutcliffe and Zeuner 1962) and unpublished transverse sections (A.J. Sutcliffe pers. comm.), probably comprised pure, or nearly pure, Bear Stratum. Thus an origin in the Bear Stratum seems almost certain. Why they were ascribed to the Hyaena Stratum in the published accounts is something of a mystery. It may be related to the discovery of other ‘warm stage’ species in that deposit, coupled with a desire to recognise a single well defined interglacial event as the theory of the time demanded, with a consequent reluctance to believe the more complex evidence in the field.

Problems also surround the rodents, which were studied by Sutcliffe and Kowalski (1976). Stuart (1982) and A.P. Currant (pers. comm.) found some of their identifications to be incorrect, notably that of Microtus nivalis (snow vole). In addition, the material ascribed by Sutcliffe and Kowalski (1976) to the Bear Stratum is
now believed by A.P. Currant to have come from the Rodent Deposit in the Lower Entrance, which cannot be correlated with the Bear Stratum. New samples of the Bear Stratum from Vivian's Vault have proved to have a completely different fauna (L. Cornish pers. comm.), suggesting that he is correct.

The Glutton Stratum is dominated by the remains of _Ursus_. With them are a mixture of species indicative of both cold and warm climates: _Rangifer_ (reindeer), _Gulo_ (wolverine), _Dicrostonyx_ (arctic lemming) and _Lemmus_ (Norway lemming) are characteristic of cold climates, whereas the presence of _Dama_ (fallow deer), _Apodemus_ (wood mouse), _Clethrionomys_ (bank vole), _Microtus agrestis_ (field vole) and bats implies warm woodland conditions (A.P. Currant 1989, pers. comm.). This fauna is clearly mixed, in accordance with the sedimentological evidence that the Glutton Stratum represents a debris flow deposit which has slumped downwards by perhaps several metres and has become mixed in the process. It is probable that before this event the Glutton Stratum was a stratified deposit similar to the overlying beds: it thus provides evidence for a complex sequence of faunas, albeit one that can probably not now be unravelled. The Glutton Stratum has also produced a single decomposed flint flake, hinting at the presence of man in the area during this period (R. Jacobi pers. comm.).
Although the Otter Stratum shows clear stratigraphic and lithological similarities to the Glutton Stratum, its fauna is significantly different. Many of the species of the Otter Stratum are also found in the Glutton Stratum. However, the Otter Stratum contains an additional element, including abundant wildfowl, *Sorex* (shrew), *Neomys* (water shrew), *Crocidura* (white-toothed shrew) and the nominate species of the deposit, *Cyrnaonyx antiqua* (clawless otter). The last is present as a single tooth in the Glutton Stratum. The shrews are characteristic of an interglacial environment, as is the presence of *Apodemus*, *Clethrionomys*, *Microtus agrestis* and *Meles* (badger) (Currant 1989, A.P. Currant pers. comm.) and suggest that the Otter Stratum is attributable to deposition in full interglacial conditions in a period poorly (or not at all) represented in the Glutton Stratum. Sutcliffe and Kowalski (1976) noted that the warm faunal elements unique to the Otter Stratum occurred in broken blocks of speleothem within the deposit, suggesting the speleothem grew during the interglacial period. This was confirmed by the author and A.P. Currant while sampling for uranium series dating.

Both the Glutton and Otter Strata lie beneath and thus predate the Bear Stratum, which contains *Hippopotamus* and can thus be referred to the Ipswichian Interglacial (see below). The conclusion that the Otter Stratum interglacial fauna predates the Ipswichian Interglacial is supported by the presence in the Otter Stratum of
Cyrnaonyx and Crocidura which are unknown in the Ipswichian (Currant 1989). The Otter Stratum fauna is unique in Britain in its abundance of Cyrnaonyx, but the presence of Crocidura strongly suggests a correlation with the Aveley Interglacial, for which this is an indicator species (Currant 1989). The occurrence of Cyrnaonyx is probably attributable to taphonomic factors. Cave deposits are well known for their taphonomic bias towards carnivores compared to open sites, due to denning activity (Stuart 1983). At present the Otter Stratum is the only British cave likely to correlate with the Aveley Interglacial; thus it is not surprising that the carnivore fauna should appear unfamiliar. Environmental factors are probably also responsible for other unusual features of this fauna. In addition to Cyrnaonyx, it also contains abundant remains of wildfowl, including Ciconia ciconia (white stork), Branta bernicla (brent goose), Mergus merganser (goosander) and Tadorna tadorna (shelduck) (Harrison 1980). The presence of large numbers of both otters and wildfowl strongly suggests the presence of a wetland habitat outside the cave during the deposition of the Otter Stratum. Notwithstanding their differences, A.P. Currant (pers. comm.) has commented that the Glutton and Otter Strata are sufficiently similar faunistically that they are probably fairly close in age.

Like the Glutton Stratum, the fauna of the Bear Stratum is dominated by bears. The microfauna (recently recovered by L. Cornish (pers. comm.) from Vivian's Vault) is of
woodland interglacial type, with *Apodemus*, *Clethrionomys*, *Microtus agrestis* and *Sorex*. The presence of *Hippopotamus* also suggests peak interglacial conditions, and a correlation with the Ipswichian interglacial for which this is an indicator species (Currant 1989). This attribution of the Bear Stratum to the Ipswichian interglacial represents a radical departure from the interpretation of Sutcliffe (1957), Sutcliffe and Zeuner (1962) and Sutcliffe and Kowalski (1976), who attributed it to a pre-Ipswichian cold stage. However, in view of the evidence from both the presence of *Hippopotamus* and the new microfauna the new interpretation seems well-founded.

The overlying Hyaena Stratum was possibly the richest deposit in the cave, yielding huge quantities of bones and teeth (Sutcliffe and Zeuner 1962). There is abundant evidence that it is a hyaena den deposit (Sutcliffe 1957), including huge quantities of *Crocuta* (spotted hyaena) remains of all ages, coprolites, and evidence of gnawing and destruction of bones of prey species (the inedible teeth and foot bones were greatly overrepresented). The presence of *Clethrionomys* and *Sorex* suggests that warm conditions prevailed over at least some of the period of accumulation of the deposit, although these species are less abundant than in the Bear Stratum. This deposit was previously assigned by Sutcliffe (1957), Sutcliffe and Zeuner (1962) and Sutcliffe and Kowalski (1976) to the Ipswichian
Interglacial due to the supposed presence of *Hippopotamus*. Since *Hippopotamus* is no longer believed to occur in the Hyaena Stratum, the deposit cannot be reliably correlated with the Ipswichian and might equally be correlated with the late stage 5 warm faunas represented in the Gower Caves (see Minchin Hole, this thesis).

The Dark Earth was almost entirely excavated by Widger, who recorded only 'teeth and jaws of various animals, mostly hyaenas' (Walker and Sutcliffe 1967). Sutcliffe and Zeuner (1962) suggested that the deposit correlates with the Elk Stratum of the external sequence (see below): this might be so, but there is little positive evidence.

The Reindeer Stratum has a fauna dramatically different from the warm faunas of the Bear and Hyaena Strata, indicating a major change in climatic conditions. It comprises a typical Devensian type cold fauna with *Rangifer, Crocuta, Dicrostonyx* and *Coelodonta* (woolly rhino). The record of *Taipa* (mole) is out of place and likely to represent a recent intrusion. Several Later Upper Palaeolithic flint flakes were also found (R.Jacobi pers. comm.). The deposit contained large quantities of *Rangifer* antlers and broken bovid ribs, which Sutcliffe (1957) also interpreted as evidence for human occupation, though A.P.Currant (pers. comm.) has suggested they represent denning activity by carnivores, probably *Lupus*.
The Reindeer Stratum of the external sequence rested upon the Elk Stratum, which appears to have represented bones worked into the top of the Head below a minor hiatus (Sutcliffe and Zeuner 1962). The fauna of the Elk Stratum is similar to that of the Reindeer Stratum, with the addition of *Cervus* (red deer), but not elk, which was a misidentification of *Cervus*.

The lower part of the Middle Tunnel deposits contain *Rangifer* (A.J. Sutcliffe, A.P. Currant pers. comm.), suggesting they are referrable to Reindeer Stratum. The possibility that Sutcliffe and Zeuner (1962) identified remnants of Reindeer Stratum as Diluvium mean that their records for the latter deposit are potentially unreliable: with the exception given below they are not listed in table 5.5. Widger noted that he encountered only rodents and bats. Sutcliffe's records for the Diluvium include *Apodemus*, which was not found in the Reindeer Stratum, and thus seems likely to belong in the Diluvium. Wall remnants of Diluvium can be seen to contain large numbers of snails, and samples taken by A.P. Currant should enable a reliable faunal list to be obtained. The records of *Apodemus* and bats suggest a Holocene age for the deposit, in accordance with its position near the top of the sequence overlying the Devensian fauna of the Reindeer Stratum.

The Rodent Deposit at the Lower Entrance cannot be stratigraphically related to the rest of the sequence.
since it was destroyed before it was adequately recorded (A.J. Sutcliffe pers. comm.). The deposit probably represents an owl pellet horizon and comprises a typical Devensian type cold stage fauna (A.P. Currant pers. comm.). It would seem likely that it represents a late intrusion into the outer end of the compaction void.

5.3.4. Age of the deposits.

The cave is currently the subject of a major interdisciplinary dating project, and several dating methods have been used. Uranium series analysis of speleothem has been carried out by H.P. Schwarcz and the author. Samples were taken for uranium series analysis by P.L. Smart but no analyses carried out: some of these samples were used by the author. Dating work has also been carried out using ESR and TL methods by the author and N. Debenham respectively. Bone from the upper part of the sequence is being ¹⁴C dated by the British Museum laboratory.

As in Three Holes Cave, the speleothems can be divided into two groups. Speleothems predating the bone deposits are usually fairly clean, massive and crystalline, and occur buried by the deposits or as detrital blocks embedded in them. Speleothems also occur interstratified with the fossiliferous sediments, and are much dirtier and often porous. Severe problems have been encountered
in attempting to date the latter. H.P. Schwarcz (pers. comm.) had problems with detrital thorium contamination and found that at least one sample (78-TRN-5) was leached and undateable. The author obtained low thorium yields from speleothems interstratified with, or incorporating bone deposits, in some cases rendering the samples undateable. Bearing in mind the diverse problems that these speleothems pose for uranium series dating, future efforts might be better applied to using another technique such as ESR or TL. This project was concerned with dating of the earlier part of the sequence, which occur closely associated with clean speleothems predating them, so effort was concentrated on dating the latter material.

Four uranium series analyses (prefix 78-TRN) were carried out by H.P. Schwarcz (pers. comm.). Ten analyses were carried out by the author (prefix TN or TC: the latter were collected by P.L. Smart, though their location was reassessed by the author). Of these analyses, one was leached and three suffered almost total thorium loss; thus ten uranium series ages have been obtained from the cave. Correction for detrital contamination was carried out using method 1 (equation 8) of Schwarcz (1980). The sample locations are shown in fig. 5.10, and details of the analyses are given in table 5.6.

TN-89-2 was a clean stalagmite boss on the wall, predating the Bear Stratum which had been deposited
Figure 5.10.

Schematic sections of Tornewton Cave showing the locations of dated speleothems. Ages prefixed 78-TRN are from H.P. Schwall (pers. comm.). Ages are in ka.
<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Yield U</th>
<th>U% Th%</th>
<th>µg/g</th>
<th>( {^{234}U} )</th>
<th>( {^{230}Th} )</th>
<th>( {^{238}U} )</th>
<th>( {^{232}Th} )</th>
<th>Age (ka)</th>
</tr>
</thead>
<tbody>
<tr>
<td>78-TRN:1</td>
<td>10 16</td>
<td>0.02</td>
<td>1.297</td>
<td>1.150</td>
<td>2.333</td>
<td>&gt;350</td>
<td></td>
<td></td>
</tr>
<tr>
<td>78-TRN:2</td>
<td>36 48</td>
<td>0.06</td>
<td>1.271</td>
<td>0.945</td>
<td>3.367</td>
<td>243</td>
<td>193-328</td>
<td>205 (148-295)*</td>
</tr>
<tr>
<td>78-TRN:4</td>
<td>33 72</td>
<td>0.07</td>
<td>0.968</td>
<td>0.435</td>
<td>7.417</td>
<td>62</td>
<td>54-71</td>
<td>54 (43-65)*</td>
</tr>
<tr>
<td>78-TRN:5</td>
<td>9 15</td>
<td>0.04</td>
<td>1.795</td>
<td>6.664</td>
<td>4.192</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

(a) Analyses by H.P. Schawrz (pers.comm.)

(b) Analyses by the author

6669 TC-4-83  48 1 0.080 | 1.046±0.029 | 1.006±0.255 | 32.8±49.0 | 495 (147-00) | -
6670 TN-89-2B 81 37 0.030 | 1.072±0.009 | 0.955±0.015 | 78.5±6.1 | 298 (273-329) | -
6671 TC-6-83B 38 6 0.026 | 1.041±0.017 | 1.089±0.044 | 26.3±4.8 | >00         | -
6712 TN-89-2C 63 42 0.032 | 1.059±0.020 | 0.863±0.024 | 42.0±5.0 | 207 (190-228) | -
6726 TN-89-3B 51 3 0.066 | 1.092±0.022 | 0.164±0.029 | 1.90±0.51 | 19 (16-23)  | 10 (5-14) |
6727 TC-11-83B 54 21 0.036 | 1.111±0.020 | 0.903±0.027 | 14.7±1.2 | 231 (208-260) | 224 (201-254) |
6732 TN-90-4B 23 .3 0.042 | 1.095±0.048 | -           | -         | -           | -
6733 TN-90-1A2 28 1 0.033 | 1.152±0.030 | -           | -         | -           | -
6735 TN-90-1CD 31 0 0.069 | 1.175±0.039 | -           | -         | -           | -
6743 TN-90-6A 81 2 0.063 | 1.160±0.017 | 0.511±0.057 | 24.1±15.4 | 76 (65-89) | -

**TABLE 5.6.**

Uranium series analyses from Tornewton Cave.

(* denotes Schawrz's corrected ages calculated using \( {^{238}Th}/^{232}Th = 1.25 \))
against a weathered break face. Its position as a relict feature hanging above the Glutton Stratum suggests that it also predates that deposit. It might be claimed that the boss had grown on the Glutton Stratum before its disruption and downward slumping but this is rendered highly improbable for several reasons. The morphology of the Glutton Stratum shows that it has slumped by at least 1.5 metres; its top was originally much higher than the boss and would have buried it. In addition there are remnants of a floor attached to the boss, fragments of which should have remained on top of the Glutton Stratum had it grown in that position: none such were found (A.J. Sutcliffe pers. comm.). Two analyses were carried out. The topmost growth layer yielded an age of 207 (190-228) ka and an age of 298 (273-329) ka was obtained from the top of the next growth layer. These provide a maximum age for the Bear Stratum and Glutton Stratum. In addition the speleothem is very clean and can only have grown in an undisturbed deep cave environment, indicating that the cave was sealed over the period bracketed by the above age estimates.

Of four detrital flowstone blocks from the Glutton Stratum, three have yielded ages of greater than 350 ka, but 78-TRN-2 was dated by H.P. Schwarcz to yield an age of 205 (148-298) ka. These blocks were incorporated in, and thus predate, the Glutton Stratum, and 78-TRN-2 confirms that this deposit postdates TN-89-2. An age of 9.7 (4.7-14.2) ka was obtained from a flowstone (TN-89-3B) which
grew on Glutton Stratum flooring the compaction void in the Main Chamber. The age of 54 (43-65) ka obtained by H.P. Scharcz from 78-TRN-4, a sample from the wall of the Main Chamber, suggests that it probably also grew in the void. These ages are consistent with the Devensian age for the void implied by the Rodent Deposit at its outer end.

Three samples from Vivian’s Vault, two of them detrital blocks from the Otter Stratum, were undateable due to almost total thorium loss. However, TC-11-83B, a flowstone drapé at the entrance to Vivian’s Vault, yielded an age of 224 (201-254) ka. This flowstone is very clean, and the cave must have been sealed during its formation. The drapé also grew over the large relict stalagmite boss at the end of the Main Chamber, and shows that the sediment beneath this boss had already been eroded away by about 224 ka; the boss must be much older. At the other end of Vivian’s Vault a somewhat unreliable age of 76 (65-89) ka was obtained for TN-90-6A (with a thorium yield of 2%). This was a thin flowstone on Hyaena Stratum and provides a minimum age for that deposit.

The ages obtained for the clean speleothems TN-89-2 and TC-11-83B show that between around 298 and 207 ka the cave was sealed. The age of around 207 ka obtained for TN-89-2C also provides a minimum age for the Glutton Stratum and overlying deposits. The Glutton Stratum is overlain by the Bear Stratum, with its Ipswichian hippo
fauna, which has been dated to oxygen isotope stage 5e (Gascoyne et al., 1981). The Glutton Stratum is therefore referrable to the period between around 207 and 130 ka, corresponding to oxygen isotope stages 7 and 6.

Although no speleothems associated with the Otter Stratum could be dated using uranium series techniques, it is possible to make some inference about its age from the above results. The Otter Stratum occupies a similar stratigraphic position to the Glutton Stratum, underlying the Bear Stratum and resting on laminated clays. This suggests that it may not be dissimilar in age to the Glutton Stratum. The only access to Vivian's Vault is via the Main Chamber (the far end is blocked by an ancient speleothem boss) so the Otter Stratum must either date from the same period as the Glutton Stratum or be much older, dating from a time before the growth of the clean speleothems in the Main Chamber. The fauna of the Otter Stratum does not support the latter interpretation since it appears to be fairly close in age to the Glutton Stratum (A.P. Currant pers. comm.). This suggests the Otter Stratum dates from the period between 207 and 130 ka, like the Glutton Stratum.

Two samples of detrital speleothem from the Otter Stratum were dated using ESR methods to try to further constrain its age. One (TN-90-1CD) proved impossible to date, since no AD could be obtained. The other, TN-90-1A2, yielded a preliminary age of 224 (172-297) ka using dosimetry.
TABLE 5.7.

Preliminary ESR analysis of a detrital speleothem block from the Otter Stratum, Tornewton Cave. The external dose rate is based on dosimetry carried out by N. Debenham at the surface and 10 cm down into the Otter Stratum, and corrected for the shallow depth of measurement using attenuation data in Debenham and Aitken (1984).

AD, accumulated dose; Ext.DR, external dose rate; Int.D, internal dose.
results provided by N. Debenham (table 5.7). This provides a maximum age for the Otter Stratum. Sutcliffe and Kowalski (1978) found the fauna in the speleothem blocks in the Otter Stratum to be interglacial in character. This was confirmed by A.P. Currant and the author, who found a *Cyrnaonyx* skull embedded in speleothem while sampling material for dating (the dated sample, TN-90-1 also contained fragmentary bone). This suggests these blocks actually date from around the time of the Aveley Interglacial and that the age given above probably provides a direct age estimate for it. This confirms and improves upon the age inferred from the uranium series results, and suggests that the Otter Stratum interglacial fauna can be correlated with oxygen isotope stage 7 (Imbrie et al. 1984). Further dates relevant to these early deposits should become available in due course, when TL dating work currently being carried out by N. Debenham is completed.

Apart from the dubious age of around 76 ka for the top of the Hyaena Stratum quoted above, no speleothem ages have been obtained for the higher part of the sequence. However 14C ages and stratigraphic considerations allow some inferences to be made. The junction between the Hyaena Stratum and the Bear Stratum was marked by speleothem bosses up to 20 cm in height, suggesting that it represents a significant hiatus. If the Bear Stratum dates from oxygen isotope stage 5e, it seems improbable that its deposition, growth of the bosses and deposition
of the Hyaena Stratum can all be attributed to this (rather short) substage. Thus it is likely that the Hyaena Stratum dates from later in isotope stage 5, a conclusion entirely consistent with the age obtained for the top of the Hyaena Stratum and by comparison with late stage 5 faunas elsewhere (see Minchin Hole, this thesis). Unfortunately none of the speleothem bosses now survive, as they would have been invaluable in dating this part of the sequence. $^{14}C$ ages of 27.4$\pm$4.8 ka (top) and 34.75$\pm$0.9 ka (base) from the Reindeer Stratum in the Main Chamber and the Middle Tunnel respectively (A. Roberts pers. comm.) suggest that this deposit is in part of Middle Devensian age; the presence within it of Later Upper Palaeolithic flints suggests that at least in places it must extend into the Devensian Late Glacial.

5.4. Discussion.

Three Holes Cave and Tornewton Cave have strikingly similar sequences with evidence of early subaerial sedimentation and speleothem growth, followed by flooding and erosion and a second cycle of subaerial sedimentation. In Tornewton Cave in particular, the early speleothems are of a complexity which suggests such cycles have occurred many times in the past, implying that some mechanism must be operating to alternately raise and lower the water table. The caves lie on a limestone ridge between two valleys, which drain the limestone block and
thus determine the height of the water table. Thus a rise in the water table implies that the valley floors must also have risen. This could have occurred by aggradation choking the valley floors with sediment, due to solifluction bringing large volumes of material down into the valleys during cold periods (Cullingford 1982). The Torbryan caves show evidence of a reactivation in the karst drainage with not only a rise in the water table but streams flowing through the caves and introducing allogenic sediments. This implies the existence of a hydrological gradient. The valleys bordering the ridge are markedly different in type. The Torbryan valley is a minor dry valley on limestone, whereas the Ambrook valley to the west has a surface stream and a much larger catchment, and is floored by slate. If the latter valley aggraded to the point where its floor lay above the dry valley to the east, water could have started to flow through the ridge producing the reactivation observed.

Such a scenario is of interest in explaining some of the features of the Tornewton fauna. The Otter Stratum has a number of species (clawless otter and wildfowl) which suggests a wetland habitat lay outside the cave. The process described above rests upon the more rapid aggradation of the Ambrook, ponding water up in the limestone until it overflowed into the Torbryan valley. This valley, with no large sediment source to fill it would probably have become marshy in such conditions. If the Otter Stratum was the first faunal deposit to
accumulate, during the waning phase of the aggradation cycle, the valley may still have provided the conditions implied by the faunas. Furthermore the lowering water table is unlikely to have fallen continuously but with periodic rises during times of flood (and perhaps also due to minor reaggradation). Such a flood could have washed out most or all of the Otter Stratum from the Main Chamber while leaving it untouched in Vivian's Vault.

In Three Holes Cave the age of the main flooding postdates around 224 ka, oxygen isotope stage 7 or later. This helps in interpreting the age of the earliest deposits of Tornewton Cave, which lies some 9 m lower and must have been flooded at the same time. It seems probable that the Laminated Clay of the latter cave dates from this phase, something that cannot be proved from speleothem ages within Tornewton. This provides further support for the stage 7 attribution of the Aveley Interglacial faunas of the Otter Stratum discussed above. It should be noted that the above interpretation does not require valley aggradation to have occurred within the interglacial; it could have occurred during the previous cold stage.

This model explains many of the features of the Torbryan Caves. However, these are extraordinarily complex sites and many details require further work, for instance the relationships between the external and internal sequences of Tornewton Cave, and the possibility of correlation.
with the valley deposits via the talus. Such work could be of considerable value in allowing direct correlation between caves.

Further information about Tornewton cave has become available since the completion of this chapter: see the Addendum (Chapter 10).
6. RHINOCEROS HOLE

6.1. Introduction.

Rhinoceros Hole is one of a small group of Pleistocene cave sites (with the Hyaena Den and Badger Hole) in the Wookey Hole Ravine on the south flank of the Mendip Hills (fig. 6.1). The ravine has been formed where the River Axe emerges from Wookey Hole, the lower end of a cave system draining a large part of the Mendip Plateau. Most of this system is in Carboniferous Limestone, but the outer part of Wookey Hole, the ravine and the ravine caves are formed in Triassic Dolomitic Conglomerate draped over the limestone on the south flank of the hills.

The short passage segments comprising Rhinoceros Hole, the Hyaena Den and Badger Hole form a tight group on the east side of the ravine about 100 m downstream from the Wookey Hole resurgence (fig. 6.1), and probably represent fragments of a downstream continuation of the latter cave. Rhinoceros Hole itself comprises an alcove in the steep hillside (probably the product of cavern collapse), with two short passages, one above the other, leading off from it. The lower passage is very close to the Hyaena Den and it is almost certain that a choked connection exists between the two caves.
Figure 6.1.

Location map of Rhinoceros Hole and adjacent caves, (after a survey by W. I. Stanton).
The Hyaena Den and Badger Hole were extensively excavated in the 19th and early 20th century by Boyd Dawkins and Balch (Dawkins 1874, Balch 1947). They removed artefacts of Middle and Early Upper Palaeolithic industries associated with abundant Devensian faunal material. Excavations in Rhinoceros Hole began somewhat later, when Balch carried out a small excavation in the cave in the early years of the 20th century. No material from this excavation survives (C. Hawkes pers. comm.) but Balch (1914) records that the site yielded remains of rhinoceros, horse and hyaena. The main bulk of the Rhinoceros Hole sediments were excavated by Professor E.K. Tratman, who turned his attention to the cave in 1970 after working in the Hyaena Den. He found a thick sequence of Devensian sediments with associated fauna and artefacts. He continued until 1976, removing the sediments to the rock floor over most of the site (C. Hawkes pers. comm.). The report of this excavation was delayed indefinitely following Tratman's death in 1977. Brief preliminary accounts were published (Tratman et al. 1971, Tratman 1975, Hawkins and Tratman 1977) but it has since become clear that there are major problems with some of the published interpretations. This account presents a new synthesis based upon detailed examination of the excavation diaries of E.K. Tratman, unpublished manuscripts by D.A. Roe and S.N. Collcutt, new faunal interpretation by A.P. Currant, and new dating work carried out by the author.
6.2. The sediments.

The sediments formed a wedge-shaped deposit completely filling the alcove and parts of the Upper and Lower tunnels. When first examined by Balch (1914) only a minute arch (presumably the top of the Upper Tunnel) was visible over the top of the deposits. He dug a pit into them but fortunately did not excavate extensively so that the UBSS (under Tratman) in their 1970 excavation were able to examine a complete sequence. A complex series of layers was revealed by the excavation: Tratman subdivided these on the basis of gross morphological and palaeontological characters, but sedimentary analysis was only carried out some years after the excavation ended, by S.N. Collcutt (1985). The following sequence was recognised (summarised from Collcutt 1985 and Tratman’s unpublished manuscript and sections), (figs. 6.2, 6.3).

(a) Layer 6(5) sands: quite clean fine to medium sand with clay balls, resting on the rock floor. Well compacted with clear and undisturbed horizontal bedding.

(b) Layer 7 (removed by excavation, hence not sampled by Collcutt 1985). A lens of reddened cave earth with abundant bone, locally developed between the sands and silts of Layer 6: elsewhere this junction is marked by a reddened layer.
Figure 6.2.

Longitudinal section of the deposits in Rhinoceros Hole, based on E.K. Tratman (unpublished sections).
Figure 6.3.

Transverse sections of the deposits in Rhinoceros Hole, based on E.K. Tratman (unpublished sections). Locations of the sections are shown in fig. 6.2.
(c) **Layer 6(1-4)** silts: compact clayey silts with fine sand in places. Much contorted but with fine laminations sometimes preserved.

(d) **Layer 5**: very stony sediment with matrix sandier towards the top and clayier towards the base. Clasts include Dolomitic Conglomerate, some calcite and common bone, and show no preferred orientation.

(e) **Layer 3aE**: very stony silty clay with calcite and Dolomitic Conglomerate clasts: bone common. This unit is quite compact and may show a preferred subhorizontal clast orientation.

(f) **Layer 3a**: clayey silt with abundant calcite and Dolomitic Conglomerate clasts, randomly or slope oriented. Fragments of a massive speleothem floor were found in this unit.

(g) **Layer 2a1**: silty clay with calcite sand and some larger calcite clasts, loose to compacted.

(h) **Layer 2ar**: clayey silt with very common calcite grit and sand: this unit is interbedded with Layer 2a1.

(i) **Layer 2a**: loose to compact clayey silt with sand, and small calcite and Dolomitic Conglomerate clasts.
(j) **Layer 3**: silty to gritty clay with small mostly Dolomitic Conglomerate clasts: quite loose.

(k) **Layer 2**: extremely loose clayey silts with altered calcite and a few Dolomitic Conglomerate clasts, and patches of vein calcite sand.

(l) **Layer 1a**: dark silt, clay and calcite sand and grit, with calcite and Dolomitic Conglomerate clasts; very loose with burrows and roots, some stone lines.

(m) **Layer 1**: sediment similar to Layer 1a but a distinct depositional event.

Parts of the deposits were disturbed by large recent animal burrows which penetrated to the base of the sequence, and had caused some mixing of fauna and artefacts.

The morphology of Layers 1-5, comprising a series of sediment lenses and wedges, thickest under the uphill wall of the alcove, suggests that they have accumulated by trapping of sediment moving downslope from the hillside above. The often loose nature of the deposits, their poor sorting with a mixture of fine silts and clays and large conglomerate and calcite clasts, and the presence of a series of bedded layers, suggests that they are subaerial cave earths, deposited by a combination of soil creep, wash and collapse (Laville 1976, Collcutt et
a). 1981, Collcutt 1986). Collcutt (1985) has noted that these separable layers are distinguished on the basis of variations in the relative proportions of their coarser fractions or on colour changes, and that they are not in fact markedly differentiated in sediment type. This is consistent with the process of accumulation by a mixture of soil creep, wash and collapse processes proposed above, since variations in the relative importance of these processes (with the occurrence of localised collapse) would result in the accumulation of just such a sequence. All the material in the sediments could reasonably have been derived from the valley side above Rhinoceros Hole, which comprises a steep earth slope over bedrock of Dolomitic Conglomerate with calcite veins. The broken speleothem fragments in Layer 3a comprise fragments of a massive crystalline flowstone floor, characteristic of those formed in a deep cave environment, which cannot have been formed in situ in Layer 3a in the alcove. Thus the speleothem is probably derived from somewhere above: its origin is further discussed below.

The silts and sands of Layer 6 are distinguished from the overlying sediments by their much better sorting, the horizontal bedded morphology of the sediment bodies and the preservation of laminated structure. These features point to these sediments being water lain (Reineck and Singh 1980, Collcutt 1985). Sedimentary analysis by Collcutt (1985) showed that the sands and silts are
differentiated by the lithology of their constituent clasts. The Layer 6 sands are lithologically diverse, and very similar to those of the Wookey Hole resurgence, with Old Red Sandstone, chert, crinoid ossicles, vein calcite, clay balls, quartz grains, FeMnAl nodules and dark minerals, suggesting that they were deposited by this river. By contrast the sand fraction of the silts is very restricted in lithology, comprising vein calcite, quartz and dark minerals, perhaps due to a more local catchment (Collcutt 1985). The presence of Layer 7 between these two units indicates that they date from two separate flooding events, since Layer 7 is a poorly sorted cave earth with fauna, of subaerial type, suggesting that the cave dried out between the deposition of the Layer 6 sands and the silts.

Part of the Lower Tunnel was found to be free of sediments, and in this void there is a remnant of flowstone floor close to the roof level (fig. 6.2). This fragment is significant since its base was some distance above the surface of the sediments below, and it cannot have grown on them. It must therefore have grown on a deposit which was washed out before the deposition of Layer 6, the inference being that the Lower Tunnel was dry before the sands of Layer 6 were deposited. Thus there is evidence in Rhinoceros Hole of a complex sequence of events with two discrete episodes of flooding which reactivated a previously dry cave, followed by
accumulation of a sequence of subaerial cave earths. The significance of this is further discussed below.

6.3. The fauna.

Faunal remains were found throughout the full thickness of sediments. Bone was generally distributed through Layers 1-5, though commoner in Layers 3aE and 5. Layer 7 was likewise rich in bone. The silt and sands of Layer 6 were almost devoid of bone (Collcutt (1985) recorded rare bone only from the top of the Layer 6 sands). Most of the fauna recorded from Layer 6 came from the reddened layer between the silts and the underlying sands (Tratman unpub. ms.). This layer occupies the same stratigraphic position as Layer 7: thus it is probable that it is contemporaneous with the latter unit.

The fauna was originally identified by S. Savage (unpub. list) upon whose records the brief published accounts (Tratman et al. 1971, Tratman 1975, Hawkins and Tratman 1977) are based. More recent work by A.P. Currant (pers. comm.) has shown some of Savage's records to be erroneous, most notably the warm stage species Hippopotamus amphibius (hippo), Palaeoloxodon antiquus (straight tusked elephant) and Dicerorhinus hemitoechus (narrow nosed rhino). The demise of this supposed interglacial fauna necessitates a radical shift in the interpretation of the site.
<table>
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<th>Species</th>
<th>Layer 1</th>
<th>Layer 1a</th>
<th>Layer 2</th>
<th>Layer 3</th>
<th>Layer 2a</th>
<th>Layer 2al</th>
<th>Layer 2ar</th>
<th>Layer 3a</th>
<th>Layer 3E</th>
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Table 6.1. Fauna of Rhinoceros Hole (A.P. Current pers. comm.)
A revised species list is shown in table 6.1. This and the description below are based on details supplied by A.P. Currant (pers. comm.). The fauna forms a coherent assemblage through the whole sequence, with no evidence of any major change in the species present over the period of deposition, or of any obviously derived elements. It comprises a classic Middle Devensian assemblage, dominated by *Ursus arctos* (brown bear), *Crocuta crocuta* (spotted hyaena), and *Coelodonta antiquitatis* (woolly rhinoceros). The presence of *Coelodonta* suggests the cave was in use as a hyaena den since this species was a preferred prey item of the latter animal.

A few species are unlikely components of a Middle Devensian mammal fauna, notably the bat and *Meles meles* (badger) which is almost certainly a Holocene intrusion. The recent animal burrows penetrating deeply into the deposit may be attributable to badgers, and would account for these anomalous elements.

During the original excavations the microfauna were not systematically collected. Most of the species recorded were recovered by S.N. Collcutt during sedimentary analyses. Thus the microfauna are under-represented: the apparently restricted distribution of some species (i.e. *Citellus* (ground squirrel)) is likely to be an artefact of the sampling scheme (A.P. Currant pers. comm.).
6.4. Artefacts.

Six unequivocal flint artefacts were found low in the Rhinoceros Hole sequence during the UBSS excavations, and are considered in detail here. Besides these, a further small fragment (M41.5/2) was found higher in the sequence in Layer 3a, and Tratman (unpub. diaries) also recorded a number of possible worked bones and limestone flakes. None of these show definite signs of utilisation (C.Hawkes pers. comm.) and they do not merit further consideration.

The six definite artefacts have been described by D.A.Roe (pers. comm. and unpublished ms). Four are referrable on typological grounds to the Middle Palaeolithic; a bout coupé handaxe (M41.5/9) and three handaxe trimming flakes (M41.5/10, M41.5/14 and M41.5/16). Of the remaining two, one (M41.5/11) is an indeterminate waste flake. The other is an unusual invasively retouched blade, which Roe suggests has some similarities with Early Upper Palaeolithic leaf points. He thus attributes the blade to the Early Upper Palaeolithic.

Most of the pieces came from Layer 6. M41.5/16 (one of the handaxe trimming flakes) was in an animal burrow in Layer 6, and was probably derived from that layer. M41.5/14 (another handaxe trimming flake) was at the
junction between Layers 5 and 6. M41.5/15, the fine retouched blade, certainly occurred in Layer 7. The remainder, including the handaxe (M41.5/9) and a handaxe trimming flake (M41.5/10) came from the reddened layer within Layer 6. The available evidence suggests that the artefacts may all belong in this reddened layer separating the sands and silts of Layer 6, or its lateral equivalent, the Layer 7 cave earth. Of the two which were not found in this position, one was certainly disturbed.

The occurrence of the retouched blade at a similar stratigraphic level to the Middle Palaeolithic handaxe might be taken to imply that they might be coeval. However Layer 7 might represent a long hiatus in the deposition of Layer 6 and there is no need to suppose that they are even broadly contemporaneous. In support of this, R. Jacobi (pers. comm.) has observed that all the implements have suffered significant mechanical damage suggesting that they may have been exposed for some time before burial.

6.5. Age of the deposits.

Speleothems occur associated with the deposits in two situations. Detrital fragments occur buried within the sediments, and in the Lower Tunnel an in situ floor has been left suspended as a relict feature in the roof above the deposits. This hanging floor, and four fragments of
detrital speleothem were sampled for uranium series analysis. The results are shown in table 6.2.

All the samples had a very low uranium content (the highest measured was 0.045 μg/g) and produced low yields of both uranium and thorium, possibly due to organic contamination (revealed by frothing during sample dissolution). In addition most samples were significantly contaminated by detrital thorium with $^{230}\text{Th}/^{232}\text{Th}$ ratios as low as 1.59. The ages were corrected for contamination using method 1 (equation 8) of Schwarcz (1980). This method is known to be unreliable when applied to grossly contaminated samples. Taking this into account, with the low uranium contents and low yields, the ages obtained must be treated with some caution. Due to the general unsuitability of the speleothem for dating, no attempts were made to analyse further samples.

The hanging speleothem in the Lower Tunnel (RH-90-1D) must predate the whole sequence, but no age was obtained due to almost total thorium loss. A broken stalactite from the top of Layer 6 (M41.9/59) yielded an age of 51 (32-71) ka; however with a thorium yield of only 1% this is perhaps best ignored. The remaining samples were obtained from Layer 3a. M41.9/29, a flowstone floor slab, yielded an age of 86 (76-97) ka. Another slab of the same floor (M41.9/26) yielded a basal age of 51 (45-56) ka and a middle age of 104 (90-120) ka. Finally a subaqueous speleothem (M41.9/8a) yielded an age of 45 (41-50) ka.
<table>
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<tr>
<th>Sample No.</th>
<th>Name</th>
<th>Yield</th>
<th>U%</th>
<th>Th%</th>
<th>μg/g</th>
<th>234U/238U</th>
<th>230Th/234U</th>
<th>230Th/232Th</th>
<th>Age (ka) Uncorrected</th>
<th>Corrected</th>
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<td>M41.9-59</td>
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<td>0.121</td>
<td>1.411±0.016</td>
<td>0.627±0.062</td>
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<td>101 (86-118)</td>
<td>51 (32-71)</td>
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<td>18</td>
<td>0.034</td>
<td>1.266±0.050</td>
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<td>2.19±0.10</td>
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<td>86 (76-97)</td>
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<td>11</td>
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<td>1.450±0.065</td>
<td>0.402±0.027</td>
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<td>54 (50-59)</td>
<td>51 (45-56)</td>
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<td>0.631±0.056</td>
<td>38.2±32.2</td>
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<td>-</td>
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**TABLE 6.2.**

Uranium series analyses from Rhinoceros Hole. Due to almost total thorium loss, no extended alpha spectrometry was carried out for RH-90-1D.
The morphology of the bases of the flowstone blocks (M41.9/26 and M41.9/29) suggests that they grew on top of subaqueous speleothem similar to, and presumably coeval with, M41.9/8a. The ages obtained are thus clearly stratigraphically inverted, confirming that there are major problems with at least some of the analyses. Detrital contamination cannot be the sole cause, since such contamination produces an overestimation of the sample’s age, but the oldest age obtained was from the cleanest sample. The cause is probably leaching of the samples, which is likely to have been more severe in detrital blocks of limited size such as these.

A plot of uranium content against calculated age for the samples (fig. 6.4) shows that the samples (M41.9/29D and M41.9/26C) with 'old' ages of around 86 to 104 ka have the lowest uranium contents. These same samples have low $^{234}\text{U}/^{238}\text{U}$ ratios (fig. 6.4). This suggests that they have been leached, since leaching tends to result both in bulk uranium loss and preferential removal of $^{234}\text{U}$. Support for this interpretation is provided by the fact that it is these samples which produced the oldest ages: uranium loss through leaching will result in an erroneously old age being obtained. By contrast the higher uranium contents and $^{234}\text{U}/^{238}\text{U}$ ratios of the remaining samples suggests they have not been leached and are more likely to produce reliable age estimates. As noted above, M41.9/59 suffered almost total thorium loss in analysis.
Figure 6.4.

Uranium series analyses from Rhinoceros Hole.

(a) Graph of uranium content against uranium series age.
(b) Graph of $^{234}$U/$^{238}$U ratio against uranium series age.
M41.9/8a-A and M41.9/26C, from the broken flowstone floor in Layer 3a, produced uncorrected ages of around 71 and 55 ka, providing a maximum age for the floor. The good agreement between the corrected ages, at around 45 and 51 ka, suggests an age for the floor of around 45 to 50 ka. An age of around 50 ka is perhaps most likely: M41.9/26C, dated at around 51 ka, is much less detritally contaminated than M41.9/8a-A. Moreover, the N.W. Europe speleothem growth record shows widespread speleothem growth occurred before 49 ka, but little from 49 to 46 ka (Baker et al. 1993), supporting an age of around 50 ka for the floor.

M41.9/8a, M41.9/26 and M41.9/29 were all fragments of a broken speleothem floor represented by many blocks in Layer 3a. They clearly predate the enclosing sediments; however, the relationship between the dated speleothems and the underlying sediments is less clear. The speleothem is unlikely to have grown in the position it now occupies since its structure shows it grew in a deep cave, but the sediments show Rhinoceros Hole was already unroofed before the deposition of Layer 5. Thus the floor must have collapsed down from above. It seems unlikely that it grew in a sealed cave on the steep slope above during the deposition of the lower part of the Rhinoceros Hole sequence. Rhinoceros Hole must have been open (probably much as it is today) before this sequence started to build up. It is difficult to imagine how another sealed cave could have existed upslope, and been
subsequently destroyed without far more associated
collapse than is evident at the site. Thus it is probable
that the floor represents a relict feature left hanging
high on the walls or in the Upper Tunnel when an earlier
fill was washed out. Subsequent collapse of this floor
would have left the jumbled mass of fragments found in
Layer 3a. This suggests that the speleothem predates the
entire sediment sequence. The age inferred above for the
floor, at around 50 ka, can thus be taken as an
indication of the maximum age of the sediments.

6.6. Discussion.

The sedimentary sequence at Rhinoceros Hole shows
considerable similarities with the other ravine caves,
the Hyaena Den and Badger Hole. At the Hyaena Den, a
fossiliferous cave earth with a rich Crocuta dominated
fauna and Middle and Early Upper Palaeolithic industries
overlay basal waterlaid sand and clay (Boyd Dawkins 1874,
Tratman 1971). In Badger Hole an Early Upper Palaeolithic
industry directly overlay waterlaid sands (Balch 1947).
Thus all the caves preserve a basic sequence of basal
water laid sediments overlain by deposits containing
fauna and artefacts of Middle to Early Upper Palaeolithic
industries.

Collcutt (1985) noted that the similarities between the
caves might suggest a similar coherent sequence in each
cave, but that considerable difficulties were posed by
the distribution of the caves, one above the other on the
hillside. Thus any direct correlation of deposits between
the caves would imply that streams were flowing at
different levels at around the same time.

A possible explanation of these features is provided by
valley aggradation. It has been inferred above that
Rhinoceros Hole was dry before the deposition of the
Layer 6 sands. The presence of a subaerial cave earth
(Layer 7) between the waterlaid sediments of the Layer 6
sands and silts implies further fluctuations of water
levels in the cave. Such periodic flooding suggests the
valley floor may have become filled with sediment, which
would have raised the water table and caused flooding.
Further support for this hypothesis is provided by the
composition of the Rhinoceros Hole Layer 6 sands, which
suggests they were deposited by the Wookey Hole stream
(Collcutt 1985) and that the valley floor lay at (or
above) the level of the cave at that time. Such a process
of valley aggradation well explains the occurrence of
water laid deposits in caves at different altitudes since
each could have been flooded within a short period as the
valley floor became choked with sediment.

The probable cause for such valley floor sedimentation
was the dry Ebbor Gorge, which debouches into the Axe
valley just downstream from the Wookey Hole ravine. This
gorge is believed to have been active during cold stages
of the Pleistocene, when permafrost and sediment choking of influent caves restored surface runoff from the Mendip plateau (Ford and Stanton 1968). The arrival of large volumes of sediment in the Axe valley would have resulted in the deposition of an alluvial fan blocking the exit from the Wookey Hole ravine. Macklin and Hunt (1988) have mapped gravels of probable Devensian age in the valley about 1 km downstream from the Wookey Hole ravine. They suggest that these gravels represent the remains of an alluvial fan fed by the Ebbor Gorge and Rookham dry valley systems, strongly supporting the above hypothesis.

The presence of water laid sediments in Badger Hole implies that aggradation might have reached at least the level of this cave at 76 m O.D., which would have deeply buried both Rhinoceros Hole (at 68 m O.D.) and the Hyaena Den (at 62 m O.D.) (Barrington and Stanton 1977). The latter two caves could have been cleared out by the stream as it cut back down through the aggradation deposits and exposed them. In both Rhinoceros Hole and the Hyaena Den, cave earths with rich Crocuta dominated faunas occur overlying water laid sediments. It seems likely that these cave earths are contemporaneous. If this is the case the thin Layer 7 cave earth in Rhinoceros Hole, which underlies the Layer 6 silts, may predate the Hyaena Den cave earth. This is of interest since Layer 7 yielded a blade referred to the Early Upper Palaeolithic, which would be expected to postdate the Middle Palaeolithic industry of the Hyaena Den. However
Layer 7 in Rhinoceros Hole was overlaid only by a thin deposit of Layer 6 silts, with a void above: the possibility that the blade is a late intrusion cannot be discounted.

Collcutt (1985) suggested that the entire Rhinoceros Hole sequence above Layer 6 had been reworked. This was apparently based upon the supposed presence of mixed warm and cold faunal elements, as well as on the loose, rather undifferentiated nature of the sediments. This interpretation is undoubtedly correct for the sediments themselves, in the sense that the accumulation of subaerial cave earths necessarily consists mostly of reworking of material from upslope by a combination of wash, soil creep and collapse. However, the fauna is now known to comprise a coherent Middle Devensian assemblage with no obviously derived elements and there is no reason to suppose it has been reworked. Furthermore, Rhinoceros Hole has much in common with a number of other British cave sites with Middle Palaeolithic industries, including (besides the Hyaena Den) Creswell (Jenkinson 1984), Kent's Cavern (Campbell and Sampson 1971) and Coygan Cave (Clegg 1969). At all these other sites Middle Palaeolithic industries similar to that at Rhinoceros Hole have been found associated with Middle Devensian cold stage faunas. Thus Rhinoceros Hole fits into a known pattern of Middle Palaeolithic occupation, increasing confidence that the deposits are in situ and contain no radically older derived fauna or artefacts.
Such assemblages have been $^{14}$C dated at Coygan Cave and Robin Hood's Cave, Creswell, yielding age estimates of around 38-40 ka (Allsworth-Jones 1986). These really lie beyond the range of reliable $^{14}$C dating, but provide a good minimum age for the Middle Palaeolithic. This is supported by the presence of such industries, with their associated faunas, below the Early Upper Palaeolithic (at Pin Hole, Creswell and Kent's Cavern: Jenkinson 1984, Campbell and Sampson 1971). The Early Upper Palaeolithic has been $^{14}$C dated to between 26 and 35 ka (Allsworth-Jones 1986, Burleigh 1986). The maximum age of the Devensian Middle Palaeolithic is far less well known and the age of less than around 50 ka tentatively inferred for Rhinoceros Hole, despite its associated problems, represents a useful addition to a meagre data set. This age agrees well with the age of around 70 ka obtained for speleothem below the Middle Palaeolithic at Pin Hole by P.Rowe (R.Jacobi pers. comm.), and the tentative attribution of the Kent's Cavern Middle Palaeolithic to less than 74 ka (this thesis).
7. MINCHIN HOLE.

7.1. Introduction.

Minchin Hole is one of a series of large littoral caves in the Carboniferous Limestone sea cliffs south of Pennard in Gower (fig. 7.1). The cave comprises a rift some 12 m high, leading into a large chamber. It contains a thick sequence of Pleistocene littoral and subaerial sediments and must have formed during an earlier period of high sea level. The present sea reaches the outer part of the cave in storm conditions, and has removed a large part of the deposits.

The sediment sequence was first examined in the mid 19th Century. In 1848 E.R. Wood began excavations in several Gower caves including Minchin Hole, the results of which were communicated by Falconer (1860). They found a rich warm stage fauna overlying marine deposited sands, and Falconer pointed out that in the Gower caves as a whole, two distinct faunas (that seen at Minchin Hole and another with cold stage species) could be distinguished.

This combination of interstratified marine and terrestrial sediments, and evidence for faunal change is of particular interest and has attracted the attention of a number of other workers since then. T.N. George (1932) conducted a small excavation near the entrance to the cave and concluded that two distinct beaches (the *Patella*
Figure 7.1.
Location map of Minchin Hole and adjacent caves.
Beach and the *Neritoides* Beach) were present, separated by a subaerial cave earth with mammals. The sequence was extended downwards by J.G. Rutter and E.J. Mason, whose unpublished excavations between 1946 and 1959 exposed a third beach deposit, the Inner Beach (Sutcliffe 1981). The latest series of excavations were directed by A.J. Sutcliffe and D.Q. Bowen between 1972 and 1981 (Sutcliffe 1981), who did much to clarify the relationships of the beach sediments. They also used amino acid racemisation analysis to confirm the evidence for at least two transgressions, and to provide estimates of their ages (Davies 1983, 1985, Bowen et al. 1986b).

They described subaerial cave earths immediately associated with the beaches (Sutcliffe 1981, Sutcliffe and Currant 1984), but paid scant attention to a thick sequence of fossiliferous sediments above them, preserved as a series of remnants adhering to the cave walls. Sutcliffe et al. (1987) published a very brief account of this sequence, drawing attention to the similarities between these sediments and those recorded in the nearby Bacon Hole, which has yielded a long record of climatic and faunal changes over the Ipswichian and Early Devensian (Currant et al. 1984, Stringer et al. 1986).

Mapping by the author has shown that the account of the Minchin Hole sediments given by Sutcliffe et al. (1987) is still oversimplified, a conclusion confirmed by A.P. Currant (pers. comm.), who is continuing to work on the mammal faunas. This chapter draws upon these disparate sources of information to provide a more
complete account of the stratigraphy and age of the deposits in Minchin Hole.

7.2. The sediments.

Sutcliffe (1981) described the sediments as comprising an Inner and Outer Talus (fig. 7.2), with the lower sediments occurring as subhorizontal beds underlyierg them. Most of the Outer Talus and the underlying deposits down to the Patella Beach have been eroded away by the sea. Sediment remnants occur on both walls (figs. 7.3, 7.4) and near the entrance to the cave at George's Rock, a large boulder by the east wall which has sediment still remaining between it and the wall (fig. 7.5). The Inner Talus is still largely intact, and has not been excavated.

The lower part of the sequence investigated by Sutcliffe and Bowen, including all units below the Patella Beach, were exposed in trenches which were backfilled at the close of their excavations and are not now accessible. Thus the descriptions (below) of these units are based on Sutcliffe (1981), Sutcliffe and Currant (1984) and Sutcliffe et al. (1987) (fig. 7.2). Existing descriptions of the sequence above the Patella Beach were inadequate, and Sutcliffe's sections (fig. 7.2) show no detail at all of this part of the sequence. The higher sequence, which is now mainly represented by wall remnants on both
Figure 7.3.

Sketch elevation of sediment remnants on the west wall of Minchin Hole.
Figure 7.4.
Sketch elevation of sediment remnants on the east wall of Minchin Hole.
Figure 7.5.

The George’s Rock sediment section, Minchin Hole. Location of the section is shown in Fig. 7.4.
sides of the cave, was mapped by the author to fill the
gap in earlier coverage (figs. 7.3, 7.4, 7.5); the
descriptions (below) of these sediments are based on this
work. The following sequence is present.

(a) **Inner Beach**: bedded sand with marine shells, resting
on the rock floor and extending up to 11.6 m O.D.
(Sutcliffe 1981).

(b) **Thin White Deposit**: on the eroded surface of the
Inner Beach, possibly a thin speleothem (Sutcliffe and
Currant 1984).

(c) **Lower Red Cave Earth**: a red clayey matrix with
angular limestone fragments. No stratification was
evident and the clasts were embedded with no preferred
orientation (Sutcliffe and Currant 1984).

(d) **Speleothem floor**: capping the Lower Red Cave Earth on
the east side of the cave (Sutcliffe and Currant 1984).

(e) **Patella Beach**: a deposit composed mainly of rounded
cobbles with some boulders, with a matrix of cemented
gravel and marine shells. Only the top of the deposit is
now accessible. Sutcliffe (1981) states that the base
rests on the rock floor near the cave entrance, but that
further inside it lies unconformably on eroded sediments
of the Lower Red Cave Earth and the Inner Beach. It
wedges out against a cliff cut in those sediments.
(f) Speleothem Floor: resting on the upper surface of the Patella Beach. The speleothem is separated from the Patella Beach by a thin veneer of breccia and sandrock.

(g) Earthy Breccia Series and Neritoides Beach; 1.5 m of sediment within which two facies can be recognised. The Earthy Breccia comprises a matrix of cemented clay/silt with sand and abundant angular limestone clasts, rich in bone in places. The second facies, the Neritoides Beach, is similar but contains in addition abundant rounded gravel and small marine shells. At George's Rock the Neritoides Beach overlies beds of Earthy Breccia (fig. 7.5): the latter contained bone deposits excavated by George (1932). On the opposite wall of the cave the Neritoides Beach can be seen interstratified between beds of Earthy Breccia (fig. 7.3). The George's Rock section was apparently missed by Sutcliffe (1981), who was unable to locate Earthy Breccia beneath the Neritoides Beach, but reported that elsewhere they grade into each other. Near the top of the Earthy Breccia Series at George's Rock is a manganese-iron stained layer.

(h) Sandrock; a well sorted deposit of clean sand without large clasts or marine shells. The sandrock forms thick beds sloping in from the cave entrance (figs. 7.3, 7.4), and occurs interbedded with lenses and thin beds of stony cave earth similar to the underlying Earthy Breccia. Near the base of the Sandrock on the east wall is a remnant of
a wedge shaped deposit of very poorly sorted limestone talus (fig. 7.4).

(j) Upper Red Cave Earth: a poorly stratified chaotic sediment composed of abundant limestone fragments and boulders (up to around 1 m in size) in cemented clay/silt matrix. A layer with abundant bone is visible 0.5 m below the top of the deposit on the west side of the cave (fig. 7.3), elsewhere represented by a notch left by the depredations of previous excavators (A.P. Currant pers. comm.).

(j) Lower Angular Breccias: cemented angular limestone debris with little fine matrix. The deposit is well bedded, and slopes steeply inwards from the entrance. An earthier lens is present in the lower part of the deposit on the west side of the cave (fig. 7.3).

(k) Speleothem Floor: caps the Lower Angular Breccias on the west side of the cave, absent on the east side.

(l) Upper Angular Breccias: cemented angular limestone debris similar to the Lower Angular Breccias. The Upper Angular Breccias are preserved as remnants high on the cave walls (figs. 7.3, 7.4) and are not now readily accessible.

(m) Speleothem Floor: capping the Upper Angular Breccias (Sutcliffe and Currant 1984).
The Inner Beach and *Patella* Beach were interpreted by Sutcliffe (1981) and Sutcliffe and Currant (1984) as an intertidal or subtidal beach, and the landward part of a storm beach respectively. They are well known for the evidence they provide of two marine transgressions, clearly separated by a period of regression represented by the Lower Red Cave Earth. Amino acid racemisation studies of molluscs have been used to confirm that these beaches date from separate transgressions and to provide a means of correlation with other beaches in S.W.Britain (Davies 1983, 1985, Bowen et al. 1986b, Hollin et al. 1993). The Inner Beach transgression must have reached to at least the 11.6 m O.D. elevation of its highest deposits. The *Patella* Beach reaches about 2 m higher than the modern beach sediments in the entrance gully, suggesting that it was deposited by a transgression to around 2 m above the present sea level (Sutcliffe et al. 1987).

The *Patella* Beach is overlain by a speleothem floor in the vicinity of George's Rock, suggesting that its deposition was followed by a period of lower sea level when marine sedimentation ceased. The thin veneer of breccia and sandrock separating the speleothem from the beach suggests there was a short interval between the regression and the commencement of deposition of the floor: however this may not have been more than a few years.
The overlying Earthy Breccia Series has features such as very poor sorting, poorly defined bedding and abundant bone which suggest that it is a subaerial cave earth gradually deposited by a combination of wash, collapse and soil creep processes (Laville 1976, Collcutt et al. 1981, Collcutt 1986). It is of considerable interest in that it also contains material of marine origin (the Neritoides Beach). George (1932) held that the Neritoides Beach was deposited by a separate transgression, but this is rendered doubtful by the lithology of the deposit. It resembles a subaerial cave earth like the Earthy Breccia, but with an additional component of rounded beach gravel and small marine shells. Sutcliffe (1981) considered the Neritoides Beach to be a regressive facies of the Patella Beach; this is clearly not so since the George's Rock section shows subaerial Earthy Breccia separating them. While the Neritoides Beach might perhaps be the upper fringe of a beach it is equally likely that the shells and gravel represent material reworked by subaerial processes from an earlier deposit. A possible source is provided by the Patella Beach, surviving remnants of which occur high on the west wall of the cave (fig. 7.3); the shells and gravel could have been reworked into the Neritoides Beach by wash processes. The predominance of small shells in the Neritoides Beach (Sutcliffe 1981) supports such an origin, since reworking by wash processes would have tended to move the smaller particles. Additional support for reworking comes from
amino acid racemisation analyses (Bowen et al. 1986b) since the amino acid ratios for shells from the Neritoides Beach and the Patella Beach are very similar, suggesting they are the same age.

The occurrence of the Sandrock as beds sloping steeply down into the cave, and the lack of rounded gravel or marine shells (which are usually present in beach sands), suggests that it is aeolian in origin. Strong winds are unlikely to have blown through the cave and the Sandrock probably represents a precipitation dune deposited when blowing sand encountered the sheltered environment of the cave entrance (Reineck and Singh 1980). Its deposition implies a substantial change in the environment to one that favoured aeolian processes. This might have been due to climatic cooling (with a reduction in vegetation cover) or due to a decrease in rainfall, but caution should be exercised in inferring too much from this deposit. There are abundant historical examples of the deposition of thick aeolian sands on the coasts of Britain in a climate which is neither cool nor dry! (e.g. Culbin Sands on the Moray Firth, Holmes 1985). Certainly the occurrence within the Sandrock of lenses and beds of cave earths similar to the Earthy Breccia Series suggests conditions remained suitable for the deposition of such sediments during hiatuses in aeolianite deposition. The Sandrock can be recognised outside the cave as a regional sediment body (Sutcliffe et al. 1987) that permits correlation with other nearby sites.
The Upper Red Cave Earth is similar to the Earthy Breccia Series. It is very poorly sorted (with sediment from clay/silt to large boulders) and shows poorly defined bedding, and a bone rich layer within the deposit suggests occupation of the cave by animals during its deposition. These features suggest it is a subaerial cave earth similar to those of the Earthy Breccia Series (Laville 1976, Collcutt et al. 1981, Collcutt 1986). The overlying Angular Breccias form a wedge shaped talus composed largely of angular limestone detritus. This suggests extensive weathering of the limestone slopes above and the accumulation of a talus cone of limestone debris at the cave entrance, but a considerable relative decrease in the input of finer material. Sutcliffe (1981) suggests that these sediments are thermoelastic screes, which seems probable since frost shattering would have generated the large volumes of angular limestone debris required. Of interest here is the speleothem floor separating the Lower and Upper Angular Breccias on the west side of the cave. Speleothems are generally considered to be indicative of warm climates (Gordon et al. 1989, Baker et al. 1993) so this implies that the cold period in which the Angular Breccias formed was broken by at least one warmer phase. Similarly the speleothem capping the Upper Angular Breccia can be attributed to the ending of this cold period.
Thus the Minchin Hole sediments preserve a long and detailed lithological record of changes in environmental conditions on the Gower coast, with evidence of multiple transgressions as well as climate change.

7.3. The fauna.

Minchin Hole has long been recognised for its rich warm stage mammal faunas (Falconer 1860) and the legacy of Wood and other fossil hunters can still be seen in the cave in the form of a wide notch where they dug out virtually all of the bone bearing layer in the Upper Red Cave Earth (A.P. Currant pers. comm.). The most comprehensive and recent examination of the faunas was carried out by A.J. Sutcliffe and A.P. Currant upon whose work Table 7.1 is based (Sutcliffe and Currant 1984, Sutcliffe et al. 1987, A.P. Currant pers. comm.).

Mammalian fossils in the lower part of the sequence are very sparse with only a large form of Microtus oeconomus (root vole) from the Lower Red Cave Earth, and no mammals reported from either beach. However both beaches contain abundant marine molluscs. Patella vulgata (limpet), Nucella lapillus (dog whelk) and Littorina littorea (edible periwinkle) occur in both the Inner Beach and the Patella Beach, Littorina littoralis (flat periwinkle) only in the Patella Beach (Bowen et al. 1986b, Sutcliffe et al. 1987). All these species are common on Gower today,
<table>
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<tr>
<th>Unit</th>
<th>Vuipes vulpes</th>
<th>Crocuta crocuta</th>
<th>Crocuta cona</th>
<th>Ursus sp.</th>
<th>Panthera leo</th>
<th>Paeanoloxodon antiquus</th>
<th>Dicerorhinus hemitoechus</th>
<th>Sus scrofa</th>
<th>Cervus elaphus</th>
<th>Dama dama</th>
<th>Microtus oeconomus</th>
<th>Microtus agrestis</th>
<th>Apodemus sylvaricus</th>
<th>Clethrionomys glareolus</th>
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<td>Angular Breccias</td>
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<td>Lower Red Cave Earth</td>
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**TABLE 7.1.**


AT; absent from the top layers of the Earthy Breccia Series/*Neritoides* Beach.

TO; present only in the top layers of the Earthy Breccia Series/*Neritoides* Beach.
implying that the beaches were deposited in similar climatic conditions to the present.

The fauna of the sediments overlying the Patella Beach is much richer. The Earthy Breccia Series has yielded a warm fauna correlated by Sutcliffe and Currant (1984) with the Ipswichian hippo fauna which, apart from the absence of the nominate species, it closely resembles. The dominance of the microfauna by *Microtus agrestis* (field vole), *Clethrionomys giareoius* (bank vole) and *Apodemus sylvaticus* (wood mouse) is particularly significant since they suggest the presence of temperate woodland outside the cave (Sutcliffe et al. 1987, Currant 1989). These species are abundant in the *Neritoides* Beach, but are lost in the highest parts of the Earthy Breccia Series, where a small form of *Microtus oeconomus* puts in an appearance. The loss of the woodland species simultaneously with the appearance of *M. oeconomus* suggests a cooler climate towards the end of the deposition of the Earthy Breccia Series (Sutcliffe et al. 1987).

No fauna is recorded from the Sandrock, but mammals reappear in the Upper Red Cave Earth, from which *Palaeoloxodon antiquus* (straight tusked elephant) and *Dicerorhinus hemitoechus* (narrow nosed rhino) have been recorded (Sutcliffe et al. 1987, A.P. Currant pers. comm.). These species are generally considered to be typical of warm stage faunas, though in the absence of a woodland
microfauna it is by no means certain that the climate was as warm as in Earthy Breccia Series times. No faunas have been recorded from the Angular Breccias.

7.4. Age of the deposits.

Three techniques have been used to attempt to date the Minchin Hole sequence: amino acid racemisation analysis of molluscs, thermoluminescence and U-series dating. Davies (1983, 1985) used amino acid racemisation analysis of molluscs to correlate the Patella Beach with Belle Hougue Cave, Jersey, which has been uranium series dated to around 121 ka (Oxygen isotope stage 5e) (Keen et al. 1981), and suggested the Patella Beach is of similar age. She found the Inner Beach to be significantly older and estimated its age at around 210 ka (oxygen isotope stage 7) by using a theoretical model of racemisation kinetics to extrapolate back from the Patella Beach. Further amino acid racemisation work was carried out by Bowen et al. (1986b) and Campbell and Bowen (1989), who reached a similar conclusion. Hollin et al. (1993) carried out temperature measurements in Minchin Hole which led them to question some of the correlations with non-cave sites proposed by Bowen et al. (1986b) and Campbell and Bowen (1989). However, Hollin et al. (1993) retain the suggested correlation of the Inner Beach with stage 7, and the Patella Beach with stage 5e. Southgate (1985) applied thermoluminescence dating of feldspars to the Inner
Beach, obtaining ages of around 114 ka for fine grains and 164-226 ka for coarse grains. He suggested that the fines could represent later infiltration and thus only provided a minimum age, and that there were problems with dose estimation for the coarse fraction, making them unreliable. N. Debenham (pers. comm.) confirms that there are substantial problems in dating old sediments by this method; however it should be noted that the results are consistent with Davies' (1983, 1985) estimation of the age of the Inner Beach.

Uranium series dating of speleothems from Minchin Hole was first attempted by H.P. Schwarcz who obtained ages of between 127 and 107 ka for a detrital speleothem resting upon the *Patella* Beach (Sutcliffe and Currant 1984). They used these results to suggest that the *Patella* Beach dates from oxygen isotope stage 5e. However this is not necessarily so since the block was detrital and could considerably predate or postdate the *Patella* Beach.

A further seven samples have been dated by P.L. Smart at Bristol since 1982 (table 7.2). The majority were analysed using the USIP spike, but some analyses were carried out using the no. 2 spike and have been recalculated by the author. An additional sample was analysed by the author (table 7.2). The majority of these samples showed significant detrital contamination and were corrected using method 1 (equation 8) of Schwarcz (1980). In addition many samples showed stratigraphically
<table>
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<tr>
<th>Sample No.</th>
<th>Name</th>
<th>Yield U%</th>
<th>Th%</th>
<th>U (µg/g)</th>
<th>¹⁴⁷⁰U</th>
<th>¹³⁶U</th>
<th>¹³⁶Th</th>
<th>¹³⁵Th</th>
<th>Age (ka) Uncorrected</th>
<th>Corrected</th>
</tr>
</thead>
<tbody>
<tr>
<td>6050A</td>
<td>MH1-82A</td>
<td>18</td>
<td>50</td>
<td>0.036</td>
<td>1.402</td>
<td>0.281</td>
<td>3.76</td>
<td>35</td>
<td>(34-36)</td>
<td>27 (26-28)</td>
</tr>
<tr>
<td>6050B</td>
<td>MH1-82B</td>
<td>24</td>
<td>15</td>
<td>0.031</td>
<td>1.366</td>
<td>0.439</td>
<td>5.10</td>
<td>61</td>
<td>(57-65)</td>
<td>52 (47-56)</td>
</tr>
<tr>
<td>6050C</td>
<td>MH1-82C</td>
<td>27</td>
<td>27</td>
<td>0.028</td>
<td>2.158</td>
<td>0.316</td>
<td>11.8</td>
<td>40</td>
<td>(38-42)</td>
<td>37 (34-40)</td>
</tr>
<tr>
<td>6050D</td>
<td>MH1-82D</td>
<td>32</td>
<td>41</td>
<td>0.020</td>
<td>1.531</td>
<td>0.517</td>
<td>15.7</td>
<td>75</td>
<td>(72-78)</td>
<td>72 (69-75)</td>
</tr>
<tr>
<td>6053A</td>
<td>MH3-82A</td>
<td>57</td>
<td>43</td>
<td>0.030</td>
<td>1.656</td>
<td>0.121</td>
<td>1.62</td>
<td>14</td>
<td>(13-15)</td>
<td>6.5 (5.2-7.8)</td>
</tr>
<tr>
<td>6053B</td>
<td>MH3-82B</td>
<td>8</td>
<td>16</td>
<td>0.093</td>
<td>1.691</td>
<td>0.062</td>
<td>2.19</td>
<td>6.9</td>
<td>(6.3-7.4)</td>
<td>3.8 (3.1-4.4)</td>
</tr>
<tr>
<td>6531</td>
<td>MH3-82C2</td>
<td>60</td>
<td>38</td>
<td>0.004</td>
<td>1.330</td>
<td>1.424</td>
<td>1.23</td>
<td>&gt;00</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6510</td>
<td>MH5-82A1</td>
<td>27</td>
<td>33</td>
<td>0.062</td>
<td>1.097</td>
<td>0.674</td>
<td>11.5</td>
<td>119</td>
<td>(114-124)</td>
<td>112 (107-118)</td>
</tr>
<tr>
<td>6513</td>
<td>MH-1982-400A1</td>
<td>59</td>
<td>7</td>
<td>0.034</td>
<td>1.357</td>
<td>0.676</td>
<td>36.5</td>
<td>114</td>
<td>(108-121)</td>
<td>-</td>
</tr>
<tr>
<td>6527</td>
<td>MH-1982-400A2</td>
<td>64</td>
<td>57</td>
<td>0.032</td>
<td>1.332</td>
<td>0.721</td>
<td>87.6</td>
<td>128</td>
<td>(122-135)</td>
<td>-</td>
</tr>
<tr>
<td>6508</td>
<td>MH-1982-400B</td>
<td>52</td>
<td>18</td>
<td>0.040</td>
<td>1.284</td>
<td>0.944</td>
<td>8.02</td>
<td>241</td>
<td>(210-283)</td>
<td>230 (198-272)</td>
</tr>
<tr>
<td>6514</td>
<td>MH-184A</td>
<td>61</td>
<td>76</td>
<td>0.066</td>
<td>1.303</td>
<td>0.710</td>
<td>33.4</td>
<td>125</td>
<td>(121-130)</td>
<td>-</td>
</tr>
<tr>
<td>6528</td>
<td>MH-184B</td>
<td>51</td>
<td>38</td>
<td>0.063</td>
<td>1.250</td>
<td>0.654</td>
<td>38.7</td>
<td>110</td>
<td>(105-114)</td>
<td>-</td>
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<tr>
<td>6529</td>
<td>MH-184C</td>
<td>83</td>
<td>39</td>
<td>0.124</td>
<td>0.995</td>
<td>1.006</td>
<td>32.9</td>
<td>0</td>
<td>(441-00)</td>
<td>-</td>
</tr>
<tr>
<td>6542</td>
<td>MH 416</td>
<td>28</td>
<td>54</td>
<td>0.087</td>
<td>1.190</td>
<td>0.601</td>
<td>9.97</td>
<td>96</td>
<td>(92-101)</td>
<td>90 (85-95)</td>
</tr>
<tr>
<td>6543</td>
<td>MH 423</td>
<td>60</td>
<td>53</td>
<td>0.062</td>
<td>1.320</td>
<td>0.794</td>
<td>2.29</td>
<td>155</td>
<td>(148-162)</td>
<td>114 (107-122)</td>
</tr>
<tr>
<td>6719</td>
<td>MH-90-2B</td>
<td>74</td>
<td>19</td>
<td>0.034</td>
<td>1.269</td>
<td>0.175</td>
<td>4.17</td>
<td>21</td>
<td>(19-23)</td>
<td>16 (14-18)</td>
</tr>
</tbody>
</table>

**TABLE 7.2.**

Uranium series analyses from Minchin Hole.
Figure 7.6.

Schematic section of the deposits in Minchin Hole, showing the locations of dated speleothems. Details of speleothem 81824 are from Sutcliffe and Currant (1984). Ages are in ka.
reversed ages suggesting leaching, or recrystallisation and post depositional crystal growth, has occurred. Many of the samples were detrital blocks or from thin speleothem floors and thus were vulnerable to these problems which tend to be worst at the edges of speleothems where they are in contact with the surrounding sediments. Where this problem was encountered the ages obtained furthest from the edges of the speleothems were taken to be the most reliable since they are least likely to have been affected. The results so obtained are consistent between samples, confirming the validity of this approach.

The locations of the dated speleothems are shown in fig. 7.6. Only one speleothem associated with the pre-\textit{Patella} Beach sediments was analysed. Two samples taken from the speleothem capping the Lower Red Cave Earth (MH416 and MH423) yielded ages of 90 (85-95) and 114 (107-112) ka. The speleothem capping the \textit{Patella} Beach at George's Rock (MH1-84) yielded a basal age of 125 (121-130) ka and an age of 110 (105-114) ka for the middle of the block. This provides a minimum age for the \textit{Patella} Beach and a maximum for the overlying Earthy Breccia Series. Another sample collected nearby, a detrital block from the Earthy Breccia Series (MH5-82) yielded an age of 112 (107-118) ka, again providing a maximum age for the Earthy breccia Series. MH-1982-400, a detrital block from the Sandrock, yielded ages of 114 (108-121) and 128 (122-135) ka.
The only speleothem found directly associated with the Upper Red Cave Earth was MH-90-2, which grew in a void (probably produced by compaction) between the sediment and the cave wall; this yielded an age of 16 (14-18) ka. The speleothem floor two metres higher at the top of the Lower Angular Breccia (MH1-82) yielded ages of 52 (47-56) and 37 (34-40) ka for its central layers. This provides a minimum age for the Lower Angular Breccia and underlying deposits, as well as a maximum age for the Upper Angular Breccia. Another speleothem floor (MH3-82), which caps the Upper Angular Breccia, yielded ages of 3.8 (3.1-4.4) and 6.5 (5.2-7.8) ka, providing a minimum age for the Angular Breccias.

The age obtained for MH1-84 suggests the Patella Beach is at least 125 ka old. It probably does not much predate the speleothem, since the cave acts as a sediment trap and the layer of sediment between the beach and the speleothem would then have been thicker. Thus this speleothem supports the suggestions of Davies (1983, 1985) Bowen et al. (1986b) and Hollin et al. (1993) that the Patella Beach dates from oxygen isotope stage 5e. The ages obtained for MH1-84 are strikingly similar to the ages (107-127 ka) obtained by H.P. Schwarcz from a detrital block resting on the Patella Beach nearby (Sutcliffe and Currant 1984). It seems possible this detrital block was a detached fragment of the same floor.
The speleothems MH1-84, MHS-82 and Schwarcz's block 81824 were all buried by the Earthy Breccia Series and thus provide minimum ages for this and later deposits. All these have yielded ages of 107-112 ka, well into oxygen isotope stage 5c, suggesting that the warm stage faunas of the Earthy Breccia Series and the Upper Red Cave Earth date from this substage or later. A minimum age for these faunas is provided by MH1-82 at around 52 ka. Thus the cave earths and sandrocks containing the warm faunas, and the Lower Angular Breccia date from around 110-50 ka, covering oxygen isotope stages 5c through to 3 (Martinson et al. 1987).

The Upper Angular Breccia lies between speleothems dated to around 37 ka (MH1-82) and 6.5 ka (MH3-82), suggesting that it is probably attributable to the Late Devensian, corresponding approximately to oxygen isotope stage 2.

7.5. Discussion.

At Minchin Hole, the lack of suitably placed speleothem in contact with the Inner Beach has prevented any attempt to date it and thus test Davies' (1983, 1985) proposal that it was deposited during oxygen isotope stage 7. However the possibility of a stage 7 transgression can be addressed at other sites in the region. Speleothem overlying a raised beach in a cave on Saddle Head near Pembroke was dated by P.L. Smart (pers. comm.). These
<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Name</th>
<th>Yield U</th>
<th>Th% ug/g</th>
<th>$^{234}\text{U}$</th>
<th>$^{238}\text{U}$</th>
<th>$^{236}\text{Th}$</th>
<th>$^{238}\text{Th}$</th>
<th>Age (ka) Uncorrected</th>
<th>Age (ka) Corrected</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Analyses from Saddle Head Cave</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6534 OPC-4B</td>
<td>62 74</td>
<td>0.077</td>
<td>1.049±0.008</td>
<td>0.843±0.010</td>
<td>18.7±0.5</td>
<td>195 (188-203)</td>
<td>190 (183-198)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6535 OPC-2A</td>
<td>31 72</td>
<td>0.139</td>
<td>1.072±0.013</td>
<td>1.004±0.021</td>
<td>346±36</td>
<td>425 (344-00)</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6540 OPC-2B1</td>
<td>19 67</td>
<td>0.125</td>
<td>1.097±0.017</td>
<td>0.823±0.018</td>
<td>91.7±6.8</td>
<td>179 (169-191)</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(b) Analyses from Ravenscliff Cave</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6717 RCC-90-2B</td>
<td>32 2</td>
<td>0.053</td>
<td>1.147±0.022</td>
<td>0.046±0.027</td>
<td>1.12±0.66</td>
<td>5.2 (2.2-8.2)</td>
<td>0.6 (0-3.7)</td>
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<td></td>
</tr>
<tr>
<td>6718 RCC-90-1A</td>
<td>16 5</td>
<td>0.045</td>
<td>1.083±0.033</td>
<td>0.136±0.018</td>
<td>2.68±0.59</td>
<td>16 (14-18)</td>
<td>10 (7-13)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**TABLE 7.3.**

Uranium series analyses from Saddle Head Cave and Ravenscliff Cave.
analyses were recounted and recalculated by the author to yield the ages shown in table 7.3, and suggest the speleothem grew around 195-179 ka. This age range falls at the end of oxygen isotope stage 7 (Imbrie et al. 1984, Martinson et al. 1987) and suggests that the beach may date from that stage, strengthening the case for a stage 7 transgression.

Minchin Hole shows a very similar sedimentary sequence to Bacon Hole, another large Pleistocene littoral cave several hundred metres to the east. Bacon Hole was excavated by C.B.Stringer, S.N.Colcutt and A.P.Currant (Currant et al. 1984, Stringer et al. 1986). Whilst this site lacks the evidence of multiple transgressions seen at Minchin Hole it has a beach deposit overlain by a series of warm mammal faunas that can be tentatively correlated with those at Minchin Hole. At Bacon Hole these sediments have been much more closely examined and better climatic and faunal information has been extracted from them (table 7.4).

Speleothems from three horizons in Bacon Hole have been dated by H.P.Schwarcz (Currant et al. 1984, Stringer et al. 1986). Fragments in the Shelly Sand yielded ages of between 129 and 116 ka. These give a maximum age for this deposit and those above it. Stringer et al. (1986) suggested that the speleothem might have grown on the underlying Sandy Cave Earth, implying an age of greater than 128 ka for that and the underlying deposits (half
<table>
<thead>
<tr>
<th>Unit</th>
<th>Lithology</th>
<th>Elurina</th>
<th>Crocuta crocuta</th>
<th>Paracynodon antiquus</th>
<th>Dicerorhinus hemitoechus</th>
<th>Equus ferox</th>
<th>Balaenoptera</th>
<th>Rangifer tarandus</th>
<th>Microtus oeconomus</th>
<th>Apodemus sylvaticus</th>
<th>Climate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speleothem</td>
<td>Calcite speleothem</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Cemented Breccias</td>
<td>Massive limestone collapse breccias with cemented horizons</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>Cold</td>
</tr>
<tr>
<td>Upper Cave Earth</td>
<td>Limestone clasts in matrix of sandy silt</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper Sands</td>
<td>Well bedded sands with shell debris; probably aeolian</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Grey Clays, Slits &amp; Sands</td>
<td>Local and wind derived sediments modified by waterlogging</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shelly Sand</td>
<td>Masses of mostly marine shell debris; probably aeolian</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sandy Cave Earth</td>
<td>Poorly sorted variable matrix with limestone clasts; local origin</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sandy Breccio-Conglomerate</td>
<td>Pebbles and sand with marine shell debris; storm beach</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td>Warm</td>
</tr>
<tr>
<td>Coarse Sands</td>
<td>Aeolian sands with some local angular limestone</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basal Pebbles</td>
<td>Lag of littoral origin, not in situ</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**TABLE 7.4.**

Bacon Hole: summary of the sequence, based on Currant et al. (1984), Stringer et al. (1986).
the analyses yielded ages of >128 ka). However there is no good evidence for this and in the absence of firm evidence that the speleothem grew on the Sandy Cave Earth, it is better merely to use the age as a maximum for the Shelly Sand and later deposits. A single age determination was also carried out on a speleothem capping the Upper Cave Earth, yielding an age of 81 (63-99) ka. Three further analyses from a floor on top of the Cemented Breccias were dated at around 12 to 13 ka.

Comparing these ages with those obtained at Minchin Hole they are entirely consistent with the correlation proposed in table 7.5. At both sites the sequence comprises a raised beach representing the maximum marine transgression, followed by two cave earths with warm type mammal faunas, separated by sediments and faunas which show evidence of a climatic deterioration. The dated speleothem at Minchin Hole strongly suggests that Davies' attribution of the beach to oxygen isotope stage 5e is correct. It has previously been concluded that deposition of the cave earths with their warm faunas extended into late stage 5 (Currant et al. 1984, Stringer et al. 1986, Sutcliffe et al. 1987) but the U-series ages obtained in Minchin Hole considerably enlarge upon those previously reported and allow the sequence to be more precisely dated.

The Earthy Breccia Series and *Neritoides* Beach in Minchin Hole (Sandy Cave Earth and Shelly Sand of Bacon Hole?)
overlies and incorporates fragments of speleothems dated to 107-112 ka. The sediments must be younger than this, and by comparison with the oxygen isotope record (Martinson et al. 1987) must date from stage 5c or later. This is in agreement with A.P. Currant's (pers. comm.) observation that the Ipswichian (stage 5e) indicator species *Hippopotamus amphibius* has not been found in these units in either cave, despite extensive excavations, and that this suggests the fauna is not the Ipswichian hippo fauna as was suggested by Sutcliffe and Currant (1984). *Hippopotamus* has only been found on Gower at Ravenscliff Cave where it occurred very low in the sequence in a position perhaps more likely to correlate with the Patella Beach than the Earthy Breccia Series. The *Hippopotamus* horizon in Ravenscliff Cave is overlain by a sandrock similar to that in Minchin Hole. U-series analysis of speleothem capping the sandrock unfortunately yielded no new dating information; the speleothem is Holocene (table 7.3).

The upper warm faunas of the Upper Red Cave Earth of Minchin Hole and Upper Cave Earth of Bacon Hole lie below speleothems dated to 81 (63-99) ka in Bacon Hole, and 52 (47-56) ka in Minchin Hole, which provide minimum ages. Comparison with the oxygen isotope record (Martinson et al. 1987) suggests that within this period there were no warm stages after stage 5a, suggesting that this fauna dates from stage 5a or earlier.
The warm faunas of Minchin Hole and Bacon Hole thus probably date from the period covered by oxygen isotope stages 5c to 5a. They record a warm-cool-warm climatic sequence and within this period there are two likely correlations with the oxygen isotope record and pollen record (Martinson et al. 1987, Behre 1989, Guiot et al. 1989, Zagwijn 1989). Either the sequence records the climatic variations seen in stage 5c alone, or a longer sequence extending into stage 5a is preserved. Two lines of evidence point towards the latter alternative. Firstly the pollen record suggests the cool period in the middle of stage 5c was not lengthy or particularly severe, in contrast to the caves where the appearance of cold stage species (such as *Mammuthus*) imply a longer cool period that allowed time for such faunal changes. Secondly the U-series ages of around 81 and 52 ka on top of and a short distance above the upper fauna suggest a relatively late date for this fauna, more consistent with stage 5a (84-74 ka) than with stage 5c (104-96 ka) (Martinson et al. 1987). This correlation suggests the cold faunas beneath might be correlated with the Stump's Cross cold fauna, which has been tentatively dated to oxygen isotope stage 5b (Sutcliffe et al. 1985).

In summary a possible scheme for the Ipswichian and Early Devensian sequence seen in the Gower Caves is shown in table 7.5. The results obtained in Minchin Hole have a number of implications. The uranium series dating results suggest the *Patella* Beach dates from oxygen isotope stage
<table>
<thead>
<tr>
<th>O.I.S.</th>
<th>Minchin Hole</th>
<th>Bacon Hole</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Speleothem</td>
<td>Speleothem</td>
</tr>
<tr>
<td>2</td>
<td>Upper Angular Breccias</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Speleothem</td>
<td>Cemented Breccias</td>
</tr>
<tr>
<td>4</td>
<td>Lower Angular Breccias</td>
<td></td>
</tr>
<tr>
<td>5a</td>
<td>Upper Red Cave Earth</td>
<td>Upper Cave Earth</td>
</tr>
<tr>
<td>5b</td>
<td>Sandrock</td>
<td>Upper Sands</td>
</tr>
<tr>
<td></td>
<td>Earthy Breccia Series (upper)</td>
<td>Grey Clays, Silts &amp; Sands</td>
</tr>
<tr>
<td></td>
<td>Neritoides Beach</td>
<td>Shelly Sand</td>
</tr>
<tr>
<td>5c</td>
<td>Earthy Breccia Series (lower)</td>
<td>Sandy Cave Earth</td>
</tr>
<tr>
<td></td>
<td>Speleothem</td>
<td></td>
</tr>
<tr>
<td>5d</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5e</td>
<td>Patella Beach</td>
<td>Sandy Breccio-Conglomerate</td>
</tr>
<tr>
<td>6</td>
<td>Lower Red Cave Earth</td>
<td>Coarse Sands</td>
</tr>
<tr>
<td>7</td>
<td>Inner Beach</td>
<td>Basal Pebbles</td>
</tr>
</tbody>
</table>

**TABLE 7.5.**

A tentative correlation between Minchin Hole and Bacon Hole. O.I.S.; oxygen isotope stage.
5e: this is also quite consistent with the aminostratigraphic evidence. The *Patella* Beach is thus correlated with the Ipswichian Interglacial. The distinctive *Hippopotamus* fauna of this stage is apparently not represented in Minchin Hole. The warm type faunas above the *Patella* Beach are all later, and must by default be referred to the Early Devensian, as Stringer *et al.* (1986) pointed out for the equivalent faunas in Bacon Hole. The dating evidence from Minchin and Bacon Holes suggests that such faunas persisted intermittently to the end of oxygen isotope stage 5, at about 74 ka before the present (Martinson *et al.* 1987) and thus existed over a significant proportion of the Devensian.
8. DISCUSSION.

8.1. Introduction.

The foregoing chapters describe results from a disparate series of sites at which dating work has been undertaken. In order to arrive at a coherent chronology it is necessary to bring these results together and combine them with those obtained by other workers. It is also essential to compare them with the results obtained by other disciplines: the current state of Pleistocene geology is such that it is not yet possible to produce a chronology using one method alone. In particular in the context of this thesis, it is necessary to consider the stratigraphic information provided by the sites themselves, and the amino acid chronology, which provides the main alternative to direct dating for the Middle and Upper Pleistocene. This is attempted below.

The orbitally tuned marine oxygen isotope record (Imbrie et al. 1984, Martinson et al. 1987) is here used as the standard record against which to attempt correlation of the British sequence. The controversy surrounding Winograd et al.'s (1992) claim (by comparison with their Devils Hole vein calcite record) that this chronology is inaccurate is discussed in the Introduction (chapter 1). In fact, over most of the last 500 ka, both records are in good agreement, suggesting that neither is grossly inaccurate (Imbrie et al. 1993). While the orbitally tuned
marine oxygen isotope record (like any chronology) is doubtless capable of refinement, it probably provides reasonable estimates of the timing of Pleistocene climatic changes, and it has yet to be proved that Devils Hole (or any other record) significantly improves upon it. It is perhaps worth noting that given the fairly low precision of alpha spectrometric U-series and ESR dating, the discrepancies (which rarely exceed 20 ka) between the marine and Devils Hole records do not actually make any difference to the correlations proposed below.

8.2. The terrestrial chronology.

8.2.1. The pre-Ipswichian chronology.

Pre-Ipswichian mammal faunas have been dated at two main sites, Tornewton Cave and Kent's Cavern (fig. 8.1). At Tornewton, an interglacial fauna referrable to the Aveley Interglacial has been dated to oxygen isotope stage 7. This agrees with the aminostatigraphic work of Bowen et al. (1989) and provides further support for the chronology originally proposed by Sutcliffe and Kowalski (1976). Together with the recent discovery of an Aveley fauna directly underlying the Ipswichian Hippopotamus fauna at Tornewton this now firmly establishes the existence of the Aveley Interglacial, and that the formal stratigraphy of Mitchell et al. (1973) and mammal chronology of Stuart (1982) are incorrect.
Figure 8.1.
Inferred age ranges for pre-Ipswichian terrestrial sites. O.I.S.; oxygen isotope stage (Imbrie et al. 1984).
Two further dated sites of this general time period are known: the lower channel at Marsworth (Green et al. 1984), and Pontnewydd Cave (Green et al. 1981, Currant 1984, Schwarcz 1984). Neither have the characteristic Aveley indicator mammals. The Pontnewydd fauna is of cold type (Green et al. 1981, Currant 1984) suggesting the deposits there date from a stadial within stage 7 or to a cold stage close in age to stage 7. The dated tufa from the Marsworth lower channel contains a temperate woodland flora including *Acer* (maple), and must have formed in peak interglacial conditions. The tufa must predate the Ipswichian Interglacial (which is represented by the upper channel higher in the Marsworth sequence), and may date from stage 7 which lies within the 1 standard deviation uncertainty of two of the three ages obtained (Green et al. 1984). This tufa possibly represents the Aveley interglacial as recognised faunally but it is equally possible that it represents a different interglacial peak within stage 7. The fauna and flora of the main channel fill must postdate the tufa (which occurred as broken blocks within it), and indicate cooler interstadial conditions with a flora dominated by *Pinus* (pine). Green et al. (1984) suggest it dates from the waning phases of the interglacial represented by the tufa, or from a distinct interstadial: if the latter interpretation is favoured, the presence of the overlying Ipswichian fauna would constrain its age to late in stage 7, or stage 6. The oxygen isotope record suggests that
the stage 7 interglacial was complex, with climatic fluctuations like those seen in stage 5. There may have been more than one period with interglacial or interstadial warm faunas within stage 7, only one of which is represented by the Aveley Interglacial *Crocidura* fauna. Marsworth may perhaps hint at the presence of such multiple warm faunas. Until recently, dating techniques have not been sufficiently precise to resolve events within stage 7, but mass spectrometric uranium series dating holds a clear potential to do so, if dateable material of sufficiently high quality can be located.

Kent’s Cavern has a Westbury fauna dated to around 300-400 ka, corresponding to somewhere in oxygen isotope stages 9 to 11. This conflicts with the currently popular models of the British Pleistocene chronology, which correlate the Anglian Glaciation with oxygen isotope stage 12, at around 450 ka (Bowen et al. 1986a, Shackleton 1987, Roberts et al. 1994). The position of the Anglian within the interglacial sequence is well known: at Ostend, a Westbury fauna lies beneath the basal Anglian till (Stuart and West 1976), and at Hoxne and Hatfield, Hoxnian lake sediments overlie Anglian tills (West 1956, Sparks et al. 1969). The clear implication from Ostend that the Westbury Interglacial predates the Anglian means that the age inferred for Kent’s Cavern, and a correlation of the Anglian with stage 12, are irreconcilable. The Kent’s Cavern ages were obtained using two effectively independent dating techniques and
should therefore not be discarded out of hand despite the low precision of the results. Thus an examination of the current chronological models is necessary.

Bowen et al. (1986a) inferred on stratigraphic grounds that the Anglian dates from stage 10 or earlier. In support for a stage 12 correlation they cited two lines of argument: that no appreciable glaciatioon is known anywhere in the northern hemisphere during stage 10; and that Shackleton and Opdyke (1973) also favoured a stage 12 Anglian (based on the oxygen isotope record). Neither statement is strictly correct. Dutch stratigraphers have correlated the Elsterian Glaciation with stage 10 (de Jong 1988). This is the largest Middle Pleistocene glaciation of continental Europe and is the presumed correlative of the Anglian (Gibbard et al. 1991).

Shackleton and Opdyke (1973), far from favouring a stage 12 correlation, actually suggest that the Elsterian (and hence by implication the Anglian) dates from stage 10. A rather more convincing argument in favour of a stage 12 Elsterian/Anglian is provided by Shackleton (1987). He noted that the oxygen isotope record suggests the stages 12 and 16 glaciations were exceptionally large, and proposed that the Elsterian glaciation occurred during stage 12. However, caution must be exercised in accepting this argument. The oxygen isotope record provides a measure of global ice volume, not of the extent of local glaciations. Glaciatioon is dependant on several factors including temperature and precipitation, and the local
maximum glaciation (as represented by the Elsterian/Anglian) may not necessarily coincide with the maximum global ice volume. From the oxygen isotope record, the stage 10 glaciation was also severe (Shackleton 1987), and it remains a reasonable candidate for correlation with the Elsterian/Anglian glaciations.

The terrestrial amino acid chronology of Bowen et al. (1989) also supports a stage 12 Anglian. This is based upon the contention that Hoxnian sites can be divided into two groups, referrable to distinct interglacials. Given that the Aveley Interglacial is correlated with stage 7, the Hoxnian sites are referred to stages 9 and 11, which would be consistent with a stage 12 Anglian. However these older amino acid results show considerable scatter and there is some doubt whether they are of sufficient precision to reliably distinguish the existence of two interglacials within the Hoxnian sites. This problem is exemplified by Waverley Wood, which is assigned to stage 15, before the Cromerian, by Bowen et al. (1989) on the basis of amino acid ratios. This is an impossibly early age by comparison with the fauna and archaeology which suggest an age close to the Hoxnian Interglacial (Shotton et al. 1993). Bowen et al. (1989) give no justification for separating the Hoxnian sites into two groups, and placing them all into a single Hoxnian Interglacial correlated with stage 9 would seem to fit the data just as well (fig. 8.2). It is perhaps significant that Hughes (1987), in an earlier extensive
Figure 8.2. The post-Cromerian terrestrial aminosтратigraphy of Bowen et al. (1989). O.I.S.; oxygen isotope stage (Imbrie et al. 1984).

(a) The chronology of Bowen et al. (1989).

(b) A possible alternative chronology.
study of amino acid ratios in terrestrial molluscs, was considerably more cautious in making detailed conclusions about the age and status of Hoxnian and earlier sites.

The lithostratigraphy and biostratigraphy of Hoxnian sites provides little support for the existence of two distinct 'Hoxnian' interglacials. Firstly, if two such interglacials exist, it has proved impossible to differentiate them on faunal or floral grounds. This is unlike all other post-Cromerian interglacials, which are clearly distinct once both floral and faunal evidence has been taken into account (West 1980, Currant 1989).

Secondly, there are problems related to Bowen et al.'s (1989) attribution of the interglacial deposits at Hoxne and Hatfield (West 1956, Sparks et al. 1969) to oxygen isotope stage 9. At both these sites the interglacial sediments were deposited in lakes and rest directly on top of the Anglian till. The stratigraphy and palynology at each site shows a continuous sequence from cold to peak interglacial conditions is represented. Such a sequence is most logically interpreted as recording the transition from glacial conditions represented by the underlying till, to the ensuing interglacial. Yet if the Anglian is correlated with stage 12 and the interglacial sediments with stage 9, then it is necessary to postulate a major hiatus at the base of the interglacial sediments at each site, spanning stages 11 and 10. If so, what caused such a neat cold to warm pollen sequence to form on top of tills 150 ka older? Such a sequence could
conceivably happen to form at one site, but it is surely stretching credulity to expect that two similar sites, with similar hiatuses of identical duration, should exist.

The obvious conclusion would seem to be that the Hoxne and Hatfield lake sediments were indeed deposited shortly after the deposition of the till. If the interglacial sediments date from stage 9, then this provides evidence for a stage 10 Anglian glaciation. If the Anglian till was deposited during stage 12, then the interglacial sediments must date from stage 11, further eroding the contention that it is possible to distinguish two distinct 'Hoxnian' interglacials on the basis of amino acid ratios. Amino acid techniques are further discussed below in the context of the sea level chronology.

Taking into account the above arguments, there would seem to be a good case for arguing for a stage 10 Anglian. Within this chronology, there is a single Hoxnian Interglacial during stage 9: the Westbury Interglacial, which is pre-Anglian, would then correlate with stage 11, well within the uncertainties of the Kent's Cavern dates. However it should be noted that this chronology is in no way proven: the Kent's Cavern dates cannot in themselves be considered sufficient evidence to settle the matter. At present it would be wise to retain both models of a stage 10 or 12 correlation for the Anglian as alternative possibilities until further evidence is obtained.
Kent's Cavern, together with Westbury (Bishop 1975) and Boxgrove (Roberts et al. 1994), has the earliest evidence of hominids so far recognised in Britain. Roberts et al. (1994), assuming the Anglian is correlated with stage 12, assign a stage 13 age to Boxgrove at about 500 ka. If the Kent's Cavern dates and a stage 10 Anglian are accepted then the earliest human presence in Britain dates from around stage 11, at around 350-400 ka. The dated Lower Palaeolithic material at Pontnewydd Cave (Green et al. 1981) and Torbryan suggest intermittent Lower Palaeolithic occupation continued at least to stage 7 and probably stage 6 (Currant 1986, Wymer 1988).

8.2.2. The post-Ipswichian chronology.

Unlike the older Pleistocene record, where the emphasis is on establishing a basic sequence and chronology of interglacials, it has been possible to examine the sequence since the Ipswichian Interglacial in more detail. The correlation of the distinctive Hippopotamus fauna of the Ipswichian interglacial with oxygen isotope 5e at around 125 ka (Gascoyne et al. 1981) is generally considered secure, but the Early and Middle Devensian has been less well known. Four sites covering this period were dated: Minchin Hole, Tornewton Cave, Kent's Cavern and Rhinoceros Hole (fig. 8.3).
Figure 8.3. Inferred age ranges for post-Ipswichian terrestrial sites. O.I.S.; oxygen isotope stage (Martinson et al. 1987).

HLC High Level Chamber.
URCE Upper Red Cave Earth.
EBS Earthy Breccia Series.
At Minchin Hole, faunas of generally warm type, with *Palaeoloxodon* (straight tusked elephant) and *Dicerorhinus* (narrow nosed rhino) have been demonstrated to have persisted through much of oxygen isotope stage 5. This supports earlier results obtained nearby at Bacon Hole where similar faunas have been dated (Stringer et al. 1986). Such faunas were certainly present during stage 5c and probably also stage 5a. Evidence for the persistence of warm faunas beyond the end of the Ipswichian Interglacial is also provided by Tornewton Cave, although it proved much more difficult to date them there. These warm type faunas do not appear to have been continuously present through this period, however; *Mammuthus* (mammoth) has been found at Bacon Hole at a horizon below the highest warm fauna (Stringer et al. 1986), and the Stump Cross *Gulo* (wolverine) fauna has also been dated to within stage 5 (possibly 5b) (Sutcliffe et al. 1985). Thus one should consider the late stage 5 faunas in terms of an alternating series of warm and cold faunas, reflecting the climatic instability of the period, but nonetheless predominantly warm in aspect.

By contrast the Devensian faunas after the end of stage 5 appear to be of universally cold type. At Kent's Cavern, Cave Earth began to be deposited before around 53 ka, and its deposition lasted until the end of the Devensian. During this period, the fauna was continuously of cold type. Some variations within this fauna, possibly related to climate, can be seen. The earliest faunas at Kent's
Cavern, which suggest very cold conditions, may date from oxygen isotope stage 4. This would place the overlying Crocuta (spotted hyaena)-Coelodonta (woolly rhino) faunas, which in turn lie beneath occupation horizons $^1^4$C dated to around 30-40ka, to stage 3. A similar result has been obtained at Rhinoceros Hole, where a Crocuta-Coelodonta fauna has been dated at less than around 50 ka and is probably also referrable to stage 3. Similar faunas are also known at Creswell where unpublished dates obtained by P. Rowe are consistent with the results described here (R. Jacobi pers. comm.). No attempt has been made to examine younger faunas here since they lie within the range of $^1^4$C dating and are more appropriately dated using that method. However the Late Devensian faunas of stage 2 (around 20 to 15 ka) were arctic in type, and probably without such species as Coelodonta and Mammuthus (Stuart 1982).

Thus there is a fundamental division visible in the Devensian faunas, with mainly warm faunas persisting to the end of stage 5, and cold faunas from then to the end of the Devensian. This is consistent with the oxygen isotope record, which shows a clear distinction between oxygen isotope stage 5 and the succeeding cold stages (4, 3 and 2) (Martinson et al. 1987). Further evidence that the faunal changes can be correlated with the oxygen isotope record is seen in Minchin Hole, where the lower and upper warm faunas can tentatively be correlated with
substages 5c and 5a, although further work would be desirable to confirm the correlations proposed.

Terrestrial climatic records have been constructed from pollen sequences in Central France, Germany, the Netherlands, Denmark and elsewhere (Woillard 1978, Behre 1989, Guiot et al. 1989, Zagwijn 1989, Guiot et al. 1993). These confirm that the stage 5c and 5a interstadials appear to have been relatively warm, with woodland vegetation. The Danish, German and Netherlands sequences (Behre 1989, Zagwijn 1989) are of particular significance because they lie close to southern Britain, and at a similar latitude. Such a continuous sequence is not yet available for Britain, but recent work has done much towards remedying this. The Chelford Interstadial has long been recognised as an Early Devensian woodland interstadial (Simpson and West 1958). A similar interstadial deposit occurs at Brimpton, where it is overlain by sediments representing a second woodland interstadial, the Brimpton Interstadial (Bryant et al. 1983). At Brimpton the two interstadial deposits are separated by a stadial deposit, confirming that they do represent separate interstadials. By comparison of their pollen sequences with the continental European record the Chelford and Brimpton Interstadials have been correlated with the Danish Brorup and Odderade Interstadials (dated to oxygen isotope substages 5c and and 5a respectively) (Bryant et al. 1983, Rendell et al. 1991). This is supported by TL and U-series dating of the Chelford
Interstadial with results that suggest that it dates from stage 5c or 5a (Rendell et al. 1991, Heijns 1992, Heijns and van der Plicht 1992).

Middle Devensian interstadials are represented in Britain by the Upton Warren Interstadial sites, originally ¹⁴C dated to around 42 ka and claimed to represent a single very brief climatic amelioration (Coope 1977). The Upton Warren sites are very different from the Chelford and Brimpton Interstadials. Although the insect faunas indicate a relatively mild climate there is no evidence of the presence of woodland at this time. The concept of a single Upton Warren Interstadial is now widely rejected and the dates believed to be erroneous. However there is no reason why a series of ages should cluster as they do around 40-45 ka if they were all completely spurious. It seems likely that some kind of 'Upton Warren complex' does exist in the Middle Devensian at around 40-55 ka, though it is probably very different from the single short interstadial once proposed. Bowen et al. (1989) have suggested on the basis of amino acid ratios that Upton Warren correlates with oxygen isotope stage 5a. However there are severe difficulties with this interpretation: in particular this would imply that the Upton Warren Interstadial should be correlated with the continental European Odderade Interstadial. The Northern European Odderade sites are at a similar latitude, and only a few hundred km from southern Britain, and cannot have been climatically very different. However, the Odderade
Interstadial is a woodland interstadial and very unlike the Upton Warren (Behre 1989); indeed, the two are so different that it is difficult to accept that they could represent the same event. Thus the concept of the Upton Warren as a Middle Devensian interstadial (or complex of interstadials) is retained here. Assuming they do date from around 40-55 ka, the Upton Warren sites can be correlated with oxygen isotope stage 3. This would imply a correlation of Upton Warren with the continental European Oerel, Denekamp or Hengelo Interstadials, which are of similar type with a predominantly herbaceous flora (Behre 1989, Zagwijn 1989).

Comparing the mammalian and vegetation records discussed above, there are clear similarities. During the Early Devensian, covering oxygen isotope stage 5 up to around 74 ka (Martinson et al. 1987), we have evidence of woodland interstadials and warm faunas during the warm substages 5c and 5a. After the end of stage 5, the woodland cover and warm fauna both disappear, and both fauna and flora are of cold type until the end of the Devensian at around 15 ka. Within stage 5 the flora and mammal faunas also show similar detailed fluctuations. The evidence in both cases suggests that warm floras and faunas were probably restricted to the warm substages (5e, 5c and 5a), with cold type stadial faunas and floras during substages 5d and 5b. Of the warm substages, 5e (the Ipswichian Interglacial) was the warmest with deciduous woodland and the full interglacial Hippopotamus
fauna. Substages 5c and 5a were significantly cooler, with coniferous woodland, and a fauna, which while generally warm in type, lacked some of the interglacial elements such as *Hippopotamus*.

An independent terrestrial British climatic record is provided by the speleothem growth record (Gordon *et al.* 1989, Baker *et al.* 1993). Since speleothem growth is greater in warm conditions this provides a proxy climatic record. There are some problems with this record. Firstly speleothem growth requires both warm temperatures and a reasonably high precipitation to occur. Thus variations in the growth rate cannot be related to a simple climatic factor but is a response to both temperature and rainfall. Secondly, the method used by Gordon *et al.* (1989) and Baker *et al.* (1993) to construct the record was to plot a probability distribution of the ages of speleothems dated in the study area. This leads to difficulties in interpretation, since it is very difficult to assess the contribution of random errors. Baker *et al.* (1993) have gone some way to address this and have established that the major variations seen in the record are genuine, but there is no way to tell if smaller peaks are real or due to statistical fluctuations in the data set. Thus the record is inherently of low precision.

In general the speleothem record is consistent with the mammalian and floral records, with generally warm
conditions during stage 5, and cooler conditions following, with an interstadial complex during stage 3. However a major point of departure is stage 5a, during which there was apparently little speleothem growth in Britain. This is discussed at some length by Baker et al. (1993) who conclude that low speleothem growth during substage 5a was probably due to increased aridity at this time, rather than a cold climate. This would be consistent with the attribution of the Brimpton Interstadial and the highest Minchin and Bacon Hole faunas to substage 5a, in that these clearly indicate a warm climate. However it would be desirable to obtain further evidence for an arid substage 5a to support Baker et al.'s (1993) conclusions.

The Devensian saw a succession of Palaeolithic cultures in Britain. The chronology of the Upper Palaeolithic cultures of the late Middle Devensian and the Late Devensian is well established using 14C dating, with an Early Upper Palaeolithic occupation at around 40-25 ka, and a Late Upper Palaeolithic occupation at around 15-10 ka (Campbell 1977, Allsworth-Jones 1986, Jacobi et al. 1986). The Middle Palaeolithic cultures of the Middle Devensian are less well known since they lie for the most part beyond the range of 14C dating. They are consistently found with cold faunas of Middle Devensian type, suggesting they must postdate the end of stage 5 at around 74 ka (Martinson et al. 1987). At a number of sites (including Kent’s Cavern and Creswell, Campbell and
Sampson 1971, Jenkinson 1984) they underlie Early Upper Palaeolithic occupation horizons, implying that they date from before around 40 ka. This implies that Middle Palaeolithic occupation dates from between 76 and 40 ka. At Rhinoceros Hole deposits tentatively concluded to postdate 50 ka contain Middle Palaeolithic artefacts, suggesting that there the occupation can be correlated with oxygen isotope stage 3, when a warmer climate would have made Britain more amenable than during the stage 4 and 2 stadials. At other sites, Kent’s Cavern and Creswell (Campbell and Sampson 1971, Jenkinson 1984), Middle Palaeolithic occupation horizons lie not far below the Early Upper Palaeolithic, suggesting they may not be very much older and supporting the conclusion that Middle Palaeolithic occupation occurred during stage 3.

8.3. The sea level chronology.

Interglacial marine transgressive sediments have been dated for this study at two sites: Minchin Hole and Berry Head (fig. 8.4). Dating of the *Patella* Beach at Minchin Hole confirmed the correlation of this beach with OIS 5e as proposed by Davies (1983, 1985). Unfortunately it was not possible to date the underlying Inner Beach which was proposed as dating from stage 7 (Davies 1983, 1985, Bowen et al., 1986b). However some support for a stage 7 age for the Inner Beach has been provided by the dating of a
Figure 8.4.


GLM Grey Laminated Muds.
BLM Brown Laminated Muds.
MB Muddy Breccia.
LB Laminate Breccia.
raised beach to stage 7 at another site in south Wales, Saddle Head Cave.

At Berry Head a much longer dated record was obtained with marine transgressions in stages 5e, 7 and 9 or earlier. The confirmation of a stage 7 transgression at Berry Head, to around the same altitude reached by Minchin Stage beaches of the amino acid chronology (including the Minchin Hole Inner Beach) suggests these beaches do indeed date from stage 7 as proposed by Davies (1983, 1985) and Bowen et al. (1986b). The latter also proposed the existence of an Unnamed Stage transgression intermediate in age between the Pennard and Minchin stages, which Campbell and Bowen (1989) later suggested dates from late in stage 7. This is not supported by the Berry Head dates. Shoalstone Beach at Berry Head is described by Bowen et al. (1986b) as their best example of the Unnamed Stage but comparison with the sea level record in the Berry Head caves suggests this beach almost certainly dates from stage 5e.

This is in agreement with the lithostratigraphy of the beaches themselves which suggests that the Unnamed Stage does not exist as a distinct transgressive event. Mottershead et al. (1987), working on the Torbay beaches, noted there is no lithostratigraphic evidence for more than the two transgressions represented by the Minchin and Pennard Stages. More serious objections come from North Devon, where Bowen et al. (1986b) report a beach
shingle containing Pennard Stage shells overlain by sandrock with shells from the supposedly older Unnamed Stage. They suggest that a later transgression introduced the Pennard Stage shells into the basal shingle, but this explanation is extremely unlikely. The only way shells could have been introduced into the shingle without disturbing the overlying sandrock is if the deposit were cliffed by the sea during stage 5e. Shells might then have lodged in voids in the deposit, penetrating perhaps a few centimetres at most. For these shells still to be present it would be necessary for no erosion of the cliffed face of the beach deposits to have occurred between stage 5 and the present. The present cliffed face of the deposits is clearly within reach of erosion by the sea and such an explanation must be regarded as untenable.

A far simpler explanation of the stratigraphy observed is that both the Unnamed and Pennard Stages date from the stage 5e transgression. If this is the case then one must question why the Unnamed Stage was proposed. The three transgressions proposed by Bowen et al. (1986b) were originally recognised on the basis of cluster analysis of amino acid ratios from raised beaches in southwest Britain. This analysis was fundamentally flawed because it used not individual shell amino acid ratios but average values for each beach. In such a dataset of amino acid ratios from beaches dating from two transgressions, one may expect three groups to be present: older beaches,
younger beaches, and beaches containing material from both transgressions (i.e. older beaches which have been reworked in the more recent transgression). Examination of Bowen et al.'s results suggests their cluster analysis may pick out these three groups, as several beaches in the Unnamed Stage group clearly represent mixed Pennard and Minchin Stage material. Furthermore, their 'best' example of an Unnamed Stage beach, the Shoalstone Beach at Berry Head, is placed by the cluster analysis not in the Unnamed Stage but in the Pennard Stage! A histogram of the amino acid ratios obtained by Bowen et al. (1986b) shows only two clear peaks, suggesting that only two major high sea levels (the Pennard and Minchin Stages) are represented in the data set, supporting this interpretation (fig. 8.5).

Certainly the Shoalstone and some other beaches show anomalously high mean amino acid ratios despite containing little or no clearly older reworked material. However Bowen et al. (1986b) fail to adequately consider the possible inter-site variations between sites of similar age. Other workers have demonstrated that minor temperature variations between sites of similar age (caused by differences in aspect, burial history etc) can lead to significant variations in the amino acid racemisation rate (Sykes 1991, Hollin et al. 1993). In addition, amino acid racemisation is a chemical process which may be affected by variations in the physiochemical environment. Isoleucine epimerisation is known to proceed
Figure 8.5.

Histogram of amino acid (D/L) ratios for marine shells from southwest Britain, based on data in Bowen et al. (1986b) (smoothed by taking the mean of each bar with those immediately adjacent).
at different rates in different species of shells, demonstrating that this is so. The question remains of whether inter-site variations could have a similar effect.

Bowen et al. (1986b) claim they encountered no such problems, but the presence of anomalous sites for which they have chosen to erect the Unnamed Stage could alternatively be interpreted as evidence of just such difficulties with the data set. If so, then the use of amino acid racemisation for the construction of detailed chronologies (whether of raised beaches or terrestrial deposits) must be approached with very much more caution than they have displayed to date.

Hollin et al. (1993) discuss the effect of temperature on the aminostages reported by Bowen et al. (1986b), and conclude that the stages proposed by the latter are not reliably distinct, and that the Unnamed Stage sites date from oxygen isotope stage 5e, in agreement with the arguments presented above. However they also argue that some of the Pennard Stage beaches of Bowen et al. are actually younger, possibly dating from late in stage 5. Late stage 5 beaches have been reported in northern France (Hallegouet and Vliet-Lanoe 1986), but there is little firm stratigraphic evidence for such a suggestion in Britain. The *Neritoides* Beach in Minchin Hole might conceivably date from such a transgression although the amino acid ratios seem to suggest that the shells within
it are of the same age as (and probably derived from) the Patella Beach. If such a transgression exists it would have to have reached a high water mark of no more than about 4.5 m O.D. as constrained by speleothem growth in the Berry Head caves. It must be said that a late stage 5 transgression in Britain cannot at present be disproved, but until further evidence is obtained the model of a single stage 5 transgression, during stage 5e, is retained here.

Sutcliffe (1985) used mammal faunas in estuarine sediments in the Thames valley to produce an interglacial marine transgressive record for the region. He inferred a transgression to just above the present sea level during the Ipswichian, to around 6 m above the present sea level during the Aveley, and to around 25 m above the present sea level during the Hoxnian Interglacial. Evidence of the sea level reached during the Westbury Interglacial is provided by the Goodwood Beach at Boxgrove near Portsmouth, where a Westbury fauna is associated with the beach at around 40 m O.D. (Roberts 1986). If an oxygen isotope stage 10 Anglian Glaciation is preferred (see above) then the Ipswichian, Aveley, Hoxnian and Westbury transgressions can be correlated with stages 5, 7, 9 and 11 respectively. If a stage 12 Anglian is the favoured model, then the Hoxnian transgression would correlate with stage 9 or 11, and the Westbury transgression with stage 13. Whichever model is
preferred, the increasing height of raised beaches with age suggests the region has been uplifted with time.

The correlation of the Anglian Glaciation with the oxygen isotope record to attempt to provide a fixed point in the British sequence has been discussed above. This approach can be equally justifiably attempted with interglacial transgressions. Indeed they are perhaps more suited to this approach, because while local maximum glaciation may not coincide with the global maximum ice volume, interglacial marine transgressions should be of similar magnitude everywhere. Shackleton (1987) discussed the interglacial peaks of the oxygen isotope record, and concluded that stages 5, 9 and 11 all had low ice volume and hence high sea levels. In contrast, during stages 7, 13, 15, 17 and 19 excess ice remained and sea levels were significantly lower. Comparing this with the transgressive record of the Thames valley and Boxgrove, in the stage 10 Anglian model, transgressions are correlated with stages 5, 7, 9 and 11. This compares well with the high relative sea levels during stages 5, 9 and 11 suggested by the oxygen isotope record. By contrast, the stage 12 Anglian model requires the Westbury transgression, the highest recorded in the British Middle Pleistocene, to be correlated with stage 13 which the oxygen isotope record suggests had a markedly low sea level (Shackleton 1987).
Thus the record of transgressions supports a model in which the Anglian Glaciation is correlated with stage 10, conflicting with the popular correlation of this Glaciation with stage 12. As noted above, although stage 12 in the oxygen isotope record appears to be the most extreme glacial maximum likely to correlate with the Anglian Glaciation, stage 10 was also severe and provides a reasonable alternative correlative. Thus a correlation of the Ipswichian, Aveley, Hoxnian and Westbury Interglacials with stages 5, 7, 9 and 11, with the Anglian falling in stage 10, would seem to provide the most likely chronology.

Comparing the altitudes of transgressions obtained in SW Britain and along the south coast to the Thames valley (fig. 8.6), it is somewhat remarkable to find a close agreement in altitude between stage 5 and 7 beaches from geographically separated sites. This agreement may well extend back to older beaches: the highest transgressive sediments at Berry Head (at around 25 metres O.D.) may correlate with either stage 9 or 11. This suggests that the whole south coast has been progressively and uniformly uplifting over the last few hundred ka. At first sight the summary graph (fig. 8.6) suggests that this uplift has not been steady, but was much more rapid before 200 ka; however this could in part be illusory, and in fact reflect a relatively low transgression during stage 7 (Shackleton 1987). The agreement in altitudes of the marine transgressions right along the south coast is
Figure 8.6.

remarkable considering that at present the Thames estuary is rapidly subsiding, whereas the SW coast is stable or is still being slowly uplifted. The most likely explanation for this is that although a long term steady uplift process is operating, it is overlaid by shorter term variations and subsidence events. The rapid modern subsidence of the Thames estuary is clearly not typical of its long term history, which has been characterised by slow uplift. It may well be due to isostatic loading by marine and estuarine sediments deposited during the modern transgression.
9. CONCLUSIONS.

Alternative versions of the British chronology discussed above are shown in tables 9.1, 9.2, 9.3. Chronology A (tables 9.1, 9.2) is favoured here. The major features of this are as follows.

(a) There is a sequence of four major post-Cromerian interglacials with associated marine transgressions. These are the Westbury, Hoxnian, Aveley and Ipswichian Interglacials, correlated with oxygen isotope stages 11, 9, 7, and 5e respectively.

(b) The Anglian Glaciation lies between the Westbury and Hoxnian Interglacials, and is correlated with oxygen isotope stage 10.

(c) The Ipswichian Interglacial was a relatively brief period restricted to oxygen isotope stage 5e. There was a marked marine transgression depositing raised beaches during the Ipswichian.

(d) The Early Devensian, during oxygen isotope stages 5d to 5a, was characterised by woodland interstadials with warm faunas, the Chelford and Brimpton Interstadials. These are correlated with oxygen isotope stages 5c and 5a, and were separated by colder periods, probably with cold faunas. There is no definite evidence in Britain of marine transgressions during the late stage 5.
interstadials, but they cannot be ruled out on present evidence.

(e) After the end of oxygen isotope stage 5, woodland cover disappeared and faunas were of universally cool or cold type until the Late Devensian at around 15 ka. Within this period, oxygen isotope stage 3 is marked by an interstadial complex represented by the Upton Warren sites, and the Middle Devensian *Coelodonta* (woolly rhino) fauna. Before and after this, during oxygen isotope stages 4 and 2, the climate was apparently much more severe, with arctic faunas.

(f) The earliest Lower Palaeolithic occupation of Britain was around the time of the Westbury Interglacial (oxygen isotope stage 11). Lower Palaeolithic occupation continued intermittently until stage 6.

(g) Man appears to have been absent during oxygen isotope stage 5 (the Ipswichian Interglacial and the Early Devensian). The Devensian Middle Palaeolithic occupation occurred during oxygen isotope stage 3, between around 60 and 40 ka, with the well dated Upper Palaeolithic occupation commencing at around 40 ka.

It must be emphasised that this chronology represents the best attempt at constructing a scheme on the available data. It will inevitably be incomplete, and new work will undoubtedly prove it to be wrong in some respects.
<table>
<thead>
<tr>
<th>Age O.I.S. ka</th>
<th>Stage</th>
<th>Mammal faunas</th>
<th>Palaeolithic occupation</th>
<th>Marine Transgressions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-4</td>
<td></td>
<td></td>
<td></td>
<td>See table 9.2.</td>
</tr>
<tr>
<td>5a-d ~119</td>
<td>IPSWICHIAN INTERGLACIAL</td>
<td>Currant (1989) Gp 1. Victoria Cave, Trafalgar Square</td>
<td>Transgression to ~ 2-5 m O.D. Berry Head, Gower, Thames Estuary</td>
<td></td>
</tr>
<tr>
<td>5e 128</td>
<td>IPSWICHIAN INTERGLACIAL</td>
<td>Currant (1989) Gp 2. Tornewton Cave, Aveley, Grays Thurrock</td>
<td>Transgression to ~ 5-10 m O.D. Berry Head, Gower Thames Estuary,</td>
<td></td>
</tr>
<tr>
<td>6 186</td>
<td>?</td>
<td>Glutton Stratum of Tornewton Cave</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 245</td>
<td>Aveley INTERGLACIAL</td>
<td>Currant (1989) Gp 2. Tornewton Cave, Aveley, Grays Thurrock</td>
<td>Transgression to ~ 25 m O.D. Thames Estuary, Berry Head?</td>
<td></td>
</tr>
<tr>
<td>9 303</td>
<td>Hoxnian INTERGLACIAL</td>
<td>Currant (1989) Gp 3. Swanscombe, Clacton</td>
<td>Transgression to ~ 40 m O.D. Boxgrove, Berry Head?</td>
<td></td>
</tr>
<tr>
<td>10 339</td>
<td>ANGLIAN GLACIATION</td>
<td>?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>423</td>
<td></td>
<td></td>
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<tr>
<th>O.I.S. ka</th>
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<th>Palaeolithic occupation</th>
<th>Marine Transgressions</th>
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<tr>
<td></td>
<td></td>
<td>HULOCENE</td>
<td>Modern fauna</td>
<td>Present sea level</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>12</td>
<td>Dimlington</td>
<td>Late Devensian cold fauna</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>24</td>
<td>Upton Warren</td>
<td>Crocuta/Coelodonta faunas of Rhinoceros</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>59</td>
<td>Interstadial</td>
<td>High Level Chamber Cave Earth cold fauna of Kent's Cavern</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>74</td>
<td>DEVENSIAN</td>
<td>Brimpton interstadial warm fauna of Minchin Hole</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5a</td>
<td>~84</td>
<td></td>
<td>Stump's Cross cold fauna?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5b</td>
<td>~93</td>
<td>Chelford</td>
<td>Earthy Breccia Series warm fauna of Minchin Hole</td>
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<td></td>
</tr>
<tr>
<td>5c</td>
<td>~105</td>
<td></td>
<td>?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5d</td>
<td>~119</td>
<td>IPSWICHIAN</td>
<td>Currant (1989) Gp 1. Victoria Cave Hippopotamus fauna</td>
<td>Transgression to ~2-5 m O.D.</td>
<td>Berry Head, Gower, Thames Estuary</td>
</tr>
<tr>
<td>5e</td>
<td>130</td>
<td>INTERGLACIAL</td>
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</table>

Despite the uncertainties, it is believed worthwhile to do this, as it provides a testable hypothesis which points to potential areas for future work (see below).

Much of this chronology is similar to those suggested recently by other workers, or represents minor modifications of them. However there are some important differences, in particular the correlation of the Anglian Glaciation with oxygen isotope stage 10, which conflicts with the popular correlation of the Anglian with stage 12. Such an interpretation for the pre-Ipswichian Pleistocene is given in chronology B (table 9.3). This differs from chronology A in the following features.

(a) The Anglian Glaciation is correlated with oxygen isotope stage 12.

(b) The Hoxnian Interglacial sites are assumed to date from two interglacial periods corresponding with oxygen isotope stages 9 and 11, in accordance with Bowen et al. (1989).

(c) The Westbury Interglacial is correlated with oxygen isotope stage 13.

Although a stage 12 correlation for the Anglian is favoured by many workers, it conflicts with the Kent's Cavern dates, which would then have to be assumed to be erroneous. In addition there are other problems with this
<table>
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<th>O.I.S.</th>
<th>Age ka</th>
<th>Stage</th>
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</thead>
<tbody>
<tr>
<td>1-4</td>
<td>~119</td>
<td>See table 9.2.</td>
</tr>
<tr>
<td>5a-d</td>
<td>128</td>
<td>IPSWICHIAN INTERGLACIAL</td>
</tr>
<tr>
<td>5e</td>
<td>186</td>
<td>?</td>
</tr>
<tr>
<td>6</td>
<td>245</td>
<td>Aveley Interglacial</td>
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<tr>
<td>7</td>
<td>303</td>
<td>?</td>
</tr>
<tr>
<td>8</td>
<td>339</td>
<td>'Hoxnian I' Interglacial</td>
</tr>
<tr>
<td>10</td>
<td>362</td>
<td>?</td>
</tr>
<tr>
<td>11</td>
<td>423</td>
<td>'Hoxnian II' Interglacial</td>
</tr>
<tr>
<td>12</td>
<td>478</td>
<td>ANGLIAN GLACIATION</td>
</tr>
<tr>
<td>13</td>
<td>524</td>
<td>Westbury Interglacial</td>
</tr>
</tbody>
</table>

**TABLE 9.3.**

chronology, detailed above in the discussion. For these reasons, in the author's opinion chronology A is more likely to prove to be correct. However, a correlation of the Anglian Glaciation with stage 10 can scarcely be considered proven, so chronology B is retained here as providing the most probable alternative to it.

There are a number of possibilities for further work. Some of the most interesting are discussed below, though the list is not intended to be exhaustive. Dealing first with the terrestrial chronology, mass spectrometric U-series dating can provide very high precision dates for the Middle and Upper Pleistocene. The method is applicable to speleothems, but requires higher quality material than is needed for alpha spectrometric U-series dating. Kent's Cavern has an abundance of clean, massive speleothem associated with the Breccia. There should be no great difficulty in obtaining high precision mass spectrometric dates from this site and thus providing a quick test of the Middle Pleistocene chronology proposed above. Similarly, mass spectrometric dating of Minchin and Bacon Holes would permit much better dating of the record of climatic and faunal changes within oxygen isotope stage 5 preserved in these caves. This would provide the opportunity to test and improve upon the chronology of events within stage 5 proposed in this thesis. Mass spectrometric dating also has the clear potential to resolve complex climatic events within oxygen isotope stage 7. However, two problems are likely
to limit the potential of mass spectrometric U-series dating of cave sites. Firstly the requirement for higher quality (cleaner) speleothem than is needed for alpha spectrometric U-series dating limits the choice of samples (although this is in part offset by the smaller sample size needed). Secondly the use of a higher precision technique does nothing to solve a fundamental problem of dating cave sequences, that the speleothem being dated may significantly predate or postdate the horizon of interest. Such difficulties may prove to be crucial. For instance, Tornewton Cave is probably the best Aveley Interglacial cave site, but it may be very difficult to date by mass spectrometric methods due to the poor quality of most of the speleothems within the sediment sequence.

The Middle Pleistocene chronology could also be tested by dating the much more abundant open sites using TL or ESR methods, which can be applied to materials such as burnt flint, tooth enamel or concretions. However because of the lower precision of these techniques, a number of sites would probably need to be dated before it became clear which of the possible chronological schemes was supported by the results.

The terrestrial chronology discussed here is based upon a sequence of distinctive interglacial warm faunas. By comparison Pleistocene cold faunas are much less well known, and it is often not possible to assign a cold
fauna to a particular cold stage with any degree of confidence. Numerous cold faunas are known in British bone caves (Sutcliffe 1969, Sutcliffe and Kowalski 1976, Hawkins and Tratman 1977, Stuart 1983, Sutcliffe 1985, Davies 1989a, 1989b). It would be of considerable interest to date some of these faunas to establish their position in the Pleistocene sequence.

Turning to the sea level chronology, mass spectrometric U-series dating again has a major potential for providing a higher resolution chronology. It could be used to confirm and improve upon the results obtained by alpha spectrometric dating at sites such as Minchin Hole, and Corbridge Cave on Berry Head. A more interesting possibility is provided by the speleothems associated with the Laminate Breccia on Berry Head. These speleothems lie at (or beyond) the age limit of alpha spectrometric dating but may be dateable using mass spectrometric techniques, and are of potentially great interest since relatively little is known of Pleistocene transgressions in Britain beyond oxygen isotope stage 7. Mass spectrometric dating could also be applied to raised beaches at open sites, some of which are cemented by clean carbonate. Dating of such carbonate cements has hitherto been made difficult or impossible by the need to obtain large samples for alpha spectrometric dating. However the much smaller sample size needed for mass spectrometric dating should solve this problem.
The long transgressive record obtained at Berry Head demonstrates the utility of the approach used there. There are two obvious possibilities for extending the record on and around Berry Head. Firstly, massive speleothems extend below low tide mark in low level caves on Berry Head. Dating of such speleothems might be useful, for instance in further constraining the height reached by possible transgressions late in oxygen isotope stage 5. Secondly, in addition to the Berry Head caves, coastal caves occur along the coast for several kilometres to the west (Oldham et al. 1978). Many of these caves lie at altitudes comparable to the high level Berry Head caves, and might provide further information about Middle Pleistocene transgressions within the 20-30 m altitude range.

Coastal cave systems also exist at other places in southwest Britain, including Plymouth in south Devon (Oldham et al. 1978), and the Pembroke district in southwest Wales (Oldham 1979). These have the potential to provide similar long transgressive records to that obtained at Berry Head. If records of comparable precision could be obtained, this might provide the means to directly compare the height reached by transgressions in different regions. A large scale study of this type, carried out in several different areas, could provide a much improved record of Middle and Upper Pleistocene transgressions in southwest Britain.
10. ADDENDUM: TORNEWTON CAVE.

Further information has become available which may necessitate extensive revision to the interpretation of Tornewton Cave (see Chapter 5, The Torbryan Caves). A.P. Currant (pers. comm.) reports that a specimen of Gulo gulo (wolverine) from the Glutton Stratum of Tornewton Cave has recently been $^{14}$C dated, yielding an age of 22.15 ka. In the light of this result Currant has reassessed the Glutton Stratum fauna, and now concludes that (apart from a few older derived elements) it dates from late in the Devensian. He retains his earlier interpretation of the Bear Stratum and Hyaena Stratum: thus these are still considered to date from a period covering the Last (Ipswichian) Interglacial to the Early Devensian.

This interpretation thus implies that the Glutton Stratum postdates the Bear and Hyaena Strata which overlie it. Comparison with the $^{14}$C dates previously obtained from the Reindeer Stratum (around 27 ka and 35 ka, A. Roberts pers. comm.) suggests the Glutton Stratum might also postdate that unit. A possible explanation for this apparent inversion of the sedimentary sequence can be provided by a scenario of Late Devensian disruption of the Main Chamber deposits. The Main Chamber sequence may initially have been much more like that now seen in Vivian's Vault, with a basal Otter Stratum, overlaid by Bear Stratum, Hyaena Stratum and a Devensian sequence. At
some time in the Late Devensian the cave flooded, washing out the basal part of the sequence, and removing virtually all of the Otter Stratum from the Main Chamber. The higher deposits remained bridging the cavity, which was then filled by a debris flow of sediment remobilised from the topmost Devensian deposits. The latter sediments may have been less compacted than those lower in the sequence and thus particularly prone to remobilisation. The cavity into which these sediments flowed (to form the Glutton Stratum) would now be represented by the void reported by Sutcliffe (1957). The Bear Stratum and Hyaena Stratum flooring the void could have arrived in its present position after the deposition of the Glutton Stratum, by collapse from sediment bodies originally roofing the void.

This interpretation could explain the differences between the sediment sequences in the Main Chamber and Vivian's Vault. However there are several problems. Firstly the $^{14}C$ date suggests the Glutton Stratum postdates the Reindeer Stratum. If this is accepted then the external sequence (which has Reindeer Stratum near the top) must have been in place before the emplacement of the Glutton Stratum. However the model outlined above suggests that the lower part of the Main Chamber sequence was washed out shortly before the emplacement of the Glutton Stratum. If so, where did this sediment go? The external sequence blocked the most plausible exit, out onto the valley floor. In addition, why should the external
sequence have remained undisturbed while the Main Chamber deposits were being so extensively disrupted? A second objection lies in the lithology of the Glutton Stratum, which contains large quantities of slate fragments and many blocks of speleothem. Where did these come from? There is no evidence in the external sequence of the availability of large volumes of slaty debris during or after Reindeer Stratum times. The speleothem blocks might conceivably have been derived from ancient wall remnants in the cave. However, this would imply that there were abundant unstable speleothem remnants on the walls of the Main Chamber, up to the time of the deposition of the Glutton Stratum at around 22 ka or later. If so, far more detrital speleothem would be expected to have been incorporated into the Bear, Hyaena and Reindeer Strata than is actually present.

A possibility that must be considered is that the single $^{14}$C date so far obtained may not accurately reflect the age of the Glutton Stratum. Assuming the date is reliable, the dated *Gulo* might represent a late intrusion which gained access to the lower part of the cave via Sutcliffe's void. If this is so then the animal could have entered the cave at any time after the deposition of the Glutton Stratum and the date actually tells us nothing about the age of the deposit as a whole. If Currant's attribution of the Glutton Stratum fauna to the Devensian is correct, then the sequence will still have to be reassessed, and the present interpretation of its
origin modified. However, it is clear that much work is necessary to properly assess Currant's suggestion. More 14C dates need to be obtained, to discover whether other Glutton Stratum species support a late age for the deposit, and some reasonable explanation for the sedimentological problems outlined above will have to be sought.

The possible attribution of the Glutton Stratum to the Devensian somewhat weakens the dating of the Otter Stratum proposed in this thesis, in that it was based partly on the contention that the Otter and Glutton Strata could be regarded as being fairly close in age. However several lines of evidence still support the dating of the Otter Stratum (and its Aveley Interglacial fauna) to oxygen isotope stage 7. Firstly, the position of the Otter Stratum beneath the Bear Stratum in Vivian's Vault suggests the Otter Stratum predates the Ipswichian Interglacial. Secondly, clean speleothem growth in the Main Chamber until around 207 ka suggests the cave was closed before that time, providing a maximum age for the Otter Stratum and its fauna. Lastly, the preliminary ESR age of around 224 ka obtained from a detrital speleothem block within the Otter Stratum is believed to provide a direct age estimate for the interglacial represented by the Otter Stratum fauna (see Chapter 5, The Torbryan Caves, for details).
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