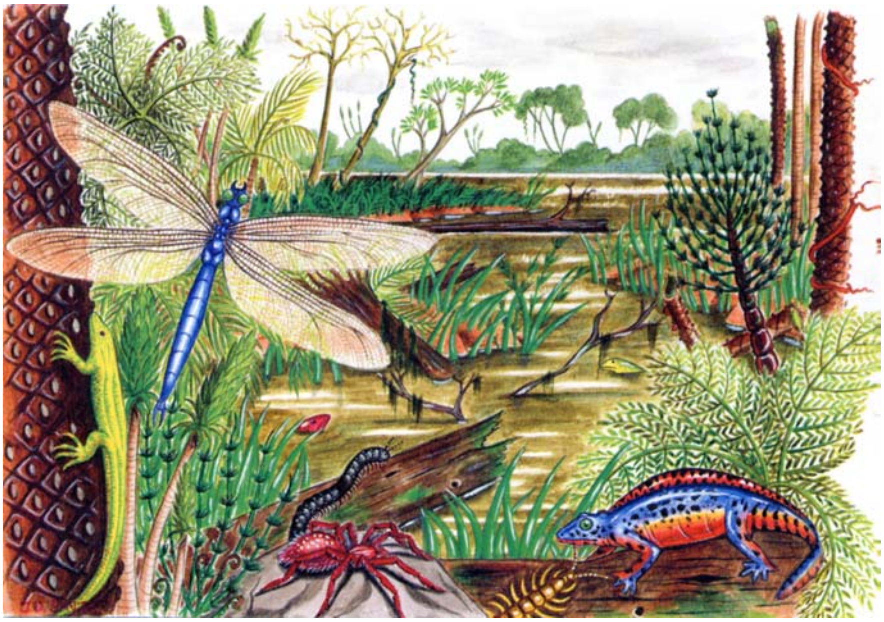
Learning from the past to influence the future

Coastal Geology & Global Change Impacts Programme

Commercial Report CR/03/009N



BRITISH GEOLOGICAL SURVEY

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COMMERCIAL REPORT CR/03/009N

Learning from the past to influence the future

B. Humphreys

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Summary

This report presents a number of case studies, ranging from periods in the distant geological past up to the present-day, which reveal the causes, and speed and magnitude of environmental changes that have affected the land area we now recognise as England. Most of all these case studies demonstrate the dynamic nature of environments over all time scales. These case studies are presented in a format to aid planners to anticipate and manage future change, by placing the gradual landscape development and subtle trends in climate-driven environmental changes seen at the present-day into the context of longer-term environmental evolution. The most urgent environmental effects to be considered over the next century are likely to be a significantly warmer temperature affecting the distribution of flora and fauna across England and the trend for rising sea level, leading to shifting coastlines in some low-lying areas. The predicted increase in the intensity and amount of winter rainfall will also lead to more frequent river flooding and increased slope and cliff instability. But this report also reveals a small risk of environmental disruption by catastrophic events, in particular volcanic eruptions, and presents the case that eventually the English landscape will be affected by a sudden return to glacial conditions.

Examples have been chosen to illustrate environmental change within a naturally evolving landscape due to coastal change, evolution of rivers and ground instability, and also of catastrophic changes caused by the onset and decline of glaciers and volcanic or tectonic events. Floral and faunal changes are treated separately, because they can be affected by all other factors causing environmental change. Where possible, modern and ancient examples are used to illustrate each process effecting environmental change.

The conservation of important geological sites, including the 1400 Sites of Special Scientific Interest (SSSIs) which include a notified geological interest, is important to preserve a record of the wide variety of environmental change that has occurred in the past. The past is very much the key to the present and future in respect of the likely speed of climate and environmental change.

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1. Introduction

Environmental change is normal and inevitable over a sufficiently long time scale. Cyclical variations in the Earth's orbit and its axis of rotation are the ultimate drivers of shifting climatic belts and environmental change. Anthropogenic effects of burning of fossil fuels and releasing greenhouse gases into the atmosphere have recently influenced natural processes of climate change and as a consequence England, in common with most other parts of the planet, seems likely to experience periods of warmer weather as a result of global warming. Historic records show that England has experienced a relatively long period of climate stability, with the "Little Ice Age" in the seventeenth century being the last period of distinctly different weather with much colder winters than at the present day. However, environmental scientists realise that Britain is currently within an interglacial period and that a return to glacial conditions at some time is inevitable. Scientific study of ice cores has shown that the current interglacial period has already lasted longer than most Quaternary interglacials, and that natural climatic changes related to fluctuating ice sheets can happen very rapidly, often in just a few years, frequently after thousands of years of relative climatic stability.

This report was commissioned by English Nature to provide examples from the recent evolution of the English landscape and from the geological record to illustrate the nature and speed of environmental change. The location of the case examples is shown on Figure 1. Although present-day changes can be measured and documented, they represent just a moment in time within the evolution of a landscape, whereas the variety of rock types and their included fossils within the geological record provide a wealth of evidence on changing climates, changing sea levels, and changing faunas (extinction and evolution).

As a note of caution, it is important to mention that the geological record is as much a record of breaks in sedimentation as it is a record of deposition. Few environments show essentially uninterrupted sedimentation records, such as some inland lakes (e.g. Yorkshire Meres, lakes in Lake District), which contain remains of contemporaneous vegetation that can capture a continuous record of climate change. However, largely through the efforts of environmental scientists, age-dated records of sedimentation from different locations can be collated to provide readily interpretable evidence of the nature and speed of past environmental change. Over the full span of geological time, the wide range of climates shown by the rock record also reflects the shifting position of continents and the natural variations of atmospheric composition.

English landscapes have been, and are likely to continue to be affected by geological processes, especially catastrophic events, occurring in another part of the country, or elsewhere in the world.

For simplicity, environmental changes are considered on two broad levels for this report:

- Ongoing geological/geomorphological processes causing long-term natural evolution of environments. Within these long-term trends there are cyclical environmental changes, such as short-lived flooding events that may cause short-term dislocation or death of individuals, populations or even species, but might be an integral and natural part of maintaining a particular habitat e.g. seasonal flooding of a water meadow.
- Catastrophic, rapid changes such as volcanic eruptions, or the advance or retreat of a glacier, that leave a permanent imprint on an environment and that can lead to species migration to new sites, or eventual extinction where there is a complete loss of species from the planet.

2 Active geomorphological processes of environmental change

2.1 THE CHANGING COAST

The long-term evolution of a coastline depends fundamentally on a number of natural environmental factors. The most important of these are relative sea level changes and sediment supply together with the underlying geology of the coast and adjacent land and sea areas. Sea level has risen globally over the last 18,000 years since the retreat of the glaciers of the last great Ice Age. During this period the rising seas and oceans have flooded the world's continental shelves in a natural process which continues, albeit at a reduced rate, to the present day. Although sea levels are rising around most of England, in parts of Cumbria and Northumberland local sea level may currently be falling relative to the land; this apparent sea-level fall is due to the continued slow isostatic rebound of land that was formerly depressed under the weight of ice sheets. Recent fears over global warming and a renewed increase in the rate of sea level rise and possible increases in storm wave action have focussed attention on the natural behaviour of our coastline over long time scales up to centuries and millennia.

Erosion and deposition at the coastline are natural responses to these environmental forces. Over recent centuries Man has intervened along the coast to provide an additional influence on the direction and magnitude of coastal change, sometimes to prevent erosion or flooding and sometimes to reclaim natural intertidal areas from the sea.

The coastal zone contains some of the most laterally variable and changeable geomorphological features in Britain. Even apparently static features such as hard rock cliffs are slowly changing. Others show seasonal variations such as beaches, or morphological modification over a range of time scales, for example the evolution of estuaries and the shifting position of tidal creeks. Sediment supply is commonly the main control on the growth and erosion of saltmarsh and sand dunes, and the growth of spits across river mouths. The broad scale picture of coastal evolution where erosion at one site may supply sediment to another part of the coast is an important consideration for maintenance and management of habitats.

The geological record also provides numerous examples of shifting coasts, and of England submerged under warm tropical seas when the landmass was located closer to the Equator. For instance, the Carboniferous period is a particularly good example; shallow seas with offshore reefs occurred across wide areas, while deltas draining from northern landmasses caused frequent adjustments in the coastline.

2.1.1 An eroding coastline

Introduction

Erosion is occurring around large parts of the coastline of England, but the rate of retreat varies enormously from coast to coast, depending on the geology of the cliffs and their exposure to wave attack. Some of the highest rates of recession are recorded by collapsing till cliffs at Holderness in Humberside and north-east Norfolk where the cliff top can retreat by several metres per year. Hard rock cliffs, such as those of the resistant Magnesian Limestone exposed on the Durham coast and sandstone cliffs on the Yorkshire coast, in contrast show very slow rates of recession. Chalk and mudstone cliffs fall between these two extremes. Not only is the overall rate of recession important, but an understanding of the mechanism of recession is critical for planning purposes. Mudstone cliffs will be prone to large-scale rotational landslides as well as more frequent mudflow events, whereas chalk cliffs retreat mainly by occasional rapid retreat events caused by rockfalls, supplemented by slow chemical erosion at intervening times.

Purpose of case study

The Holderness coastline of Humberside is used as an example of a highly dynamic coastline, in relentless retreat in its natural state (Figure 2). This example also shows the significance of cliff erosion for coastline accretion in Humberside, Lincolnshire and Norfolk.

Description of study area

The Holderness coast stretching for over 50 km from Spurn Head at the mouth of the Humber Estuary in the south to the Chalk headland of Flamborough Head in the north is renowned for its receding coastline. Most of the central part of the Holderness coast from Kilnsea to Bridlington consists of till cliffs up to 38 m high that are undefended. Long-term recession rates are typically 1.5 m per year (Figure 3). The rapid recession of the cliffs results in the supply of large quantities of sediment to the beaches and the nearshore coastal waters. The dominant longshore transport direction along this coast is to the south.

Cliff erosion on the Holderness coast is due to a combination of subaerial weathering and toe erosion by waves which causes slope instability and results in frequent small slumps a few tens of metres in width. Rates of cliff top recession thus show considerable lateral variation over short time periods.

Evidence of past change

Valentin (1971) determined coastal recession for a 100-year period by comparison of field measurements with old Ordnance Survey maps. Measurements were spaced at approximately 200 m along the coast. The average recession rates show considerable spatial variation (Figure 3). Low values at Bridlington, Hornsea and Withernsea result from the construction of “hard” defences to protect the towns. There is a trend for the erosion rate, on average, to increase southwards along the unprotected coastline.

Impacts of past and present change

Loss of land to the sea along the Holderness coast has been occurring from about 6000 years ago when the rising post-glacial sea level approached present levels. In addition to the extensive loss of agricultural land, historic records indicate that at least thirty small towns and villages have been lost to the sea since Roman times. Some towns have been relocated westward, following the loss of Medieval Withernsea and substantial loss of houses at Hornsea. Construction of sea defences in the second half of the nineteenth century to protect the towns of Bridlington, Hornsea, new Withernsea and Aldbrough has been effective, but has also served to increase erosion downdrift of the towns. In recent years the continuous erosion has been seen as a threat to the North Sea gas terminal at Easington, which was built in 1967 without due regard to local cliff recession rates.

The erosion of the Holderness cliffs is beneficial to beaches and coastal habitats further south. The eroding till cliffs release mud, sand and occasional pebbles to the nearshore zone. The coarser sand and pebbles are transported southwards by littoral drift and contribute to the maintenance of the sand and shingle spit at Spurn Head. Coastal currents transport the fine-grained sediment as suspended load away from Holderness. The majority of mud in the southern North Sea is ultimately derived from erosion of the till cliffs of Holderness in Yorkshire (smaller quantities are supplied from the till cliffs of Norfolk and from air-blown dust), which is subsequently carried for large distances south and east into the southern North Sea basin. A considerable proportion of this fine sediment is deposited on the mudflats of the Humber Estuary, in the Wash and on the North Norfolk coast. This deposition of mud facilitates growth of saltmarsh, in particular behind beach and dune barriers such as those of Scolt Head Island and Blakeney Point, thereby supporting the unique saltmarsh flora and rich wildfowl populations of the area. A map showing the broad transport directions of fine sediment in part of the southern North Sea is shown in Figure 4.

Further evidence from the geological record

Retreating coastlines by their very nature are erosional environments and are therefore unlikely to leave much evidence of their existence in the geological record. Their former existence is usually inferred from the distribution of basal sediments of marine transgressions or marine flooding events, usually represented by coarse-grained lag deposits. The early Holocene rise in sea level, and gradual encroachment of the shoreline landward, is marked by a distinctive gravel lag now covering much of the sea floor around England. Such basal lags, recording the landward shifting coastline, are common throughout the geological record and often include phosphatic pebbles, reworked shell fragments and concentrations of green grains of a mineral known as glauconite. The sandy lags produced as the early Cretaceous sea encroached over structural highs in southern England exhibit these features.

Occasional fossil clifflines are preserved in the geological record. One of the best known examples in England is the buried cliff of Holderness. This Chalk cliffline stretches from Hessle near Hull to Sewerby near Bridlington and is covered by till. This cliffline indicates the position of the coast during the Ipswichian interglacial when the sea extended much further inland than it does today. At its foot is a raised beach, a metre above present-day sea level. The presence of this fossil Chalk cliffline indicates that the current recession of the Holderness cliffs will show a tendency to continue eroding fast for thousands of years until the cliff retreat is slowed by the presence of more resistant bedrock.

Implications and management options for the future

A sound knowledge of cliff retreat processes allows judgment of whether cliff retreat can be managed, by a process of monitoring and selected slope remediation, as occurs at Scarborough. Alternatively, it may suggest that cliff retreat would be futile and too expensive to prevent in the local context as in the case for long sections of the till cliffs of Holderness and for the Chalk cliffs at Birling Gap in Sussex.

Whereas at Birling Gap there was a need to built houses close to the cliff top for coastguards, many houses have been built in England in the past century, especially in the 1930s, close to actively eroding cliff edges in order to benefit from the best sea views. Although planning regulations exist today to restrict cliff top developments in inappropriate locations, the likelihood that recession rates could be enhanced in the future by the effects of climate change means that some properties are still being built on “at-risk” cliff top localities. The DEFRA-funded Futurecoast project now provides all local authorities with the latest forward projection of coastal change trends for the next 100 years for the whole of England and Wales. This should help to ensure that coastal developments are not built in unsuitable localities.

Local councils in coastal areas are generally aware of the environmental and social consequences of coastal retreat, and in many cases are conducting their own studies of long-term coastal evolution. But the general public may remain uninformed of some aspects of coastal retreat such as the rate of retreat, the broad scale picture of coastal evolution where erosion at one locality may supply sediment to another part of the coast. For example, public lobbying for coastal defences to impede cliff recession at a site where properties are not directly at risk could cut off the supply of sediment supporting the maintenance of important coastal habitats, and indeed may induce erosion in adjoining sections of coastline. English Nature is aiming to raise awareness of the inherently changeable nature of the coastline and the benefits of allowing cliffs to erode and for coastlines to evolve naturally.

2.1.2 An accreting coastline

Introduction

Accreting coasts are typified by a seaward migration of the coastline which continues over a significant period of time. This is usually the result of deposition which is sufficiently rapid to outpace the effects of local sea level rise. Where local land movements serve to counteract some or all of the sea level rise this result is more easily achieved than where land subsidence serves to enhance the rate of sea level rise. Examples of landforms on accreting coasts include deltas which form where high rates of sediment supply from a river mouth form a broadly triangular or ‘delta’ shaped sediment body which builds out across the adjacent continental shelf. Accretion is typical within estuaries and other sheltered coastal embayments which act as sediment traps allowing the broad and often rapid accumulation of intertidal flat sediments. Other examples of accretional coastal landforms on the open coast include beach plains which form by the successive seaward migration of beach ridges as in the case of the Dungeness foreland which is described below. Dune fields are often associated with this type of accretionary coast. Spits, which often form at the mouths of inlets and estuaries, are another form of accretional coastal feature which share many similarities with the development of beach plains but which accrete along rather than at right angles to the coastline and are typically associated with sediment supplied by eroding coastlines.

Purpose of case study

Accreting coasts present both hazards and opportunities to Man and for wildlife. Accretion may present a hazard to the safe navigation of vessels in and out of ports and harbours and has often led to human interventions with varying degrees of success. The accretion of sediments within estuaries and embayments may change the hydrodynamic function of the channels at the mouth by reducing tidal flows which then acts to reduce the natural scour of the channel and promote further accretion. Accretion in some areas changes the plan shape of the coastline which can then have significant effects on the wave action or sediment transport along adjacent sections of the coastline. In some places accretion takes place in front of cliffs which were formerly eroding thus reducing or completely stopping the erosion and the natural supply of sediment which they yielded. Accretion creates new areas of terrestrial coastal habitat which supports plants and animals, particularly pioneer species, which are adapted to the rapid environmental changes which typify this dynamic area.

Description of study site

Dungeness is a large headland of low-lying land on the English Channel coast of Kent. The headland is broadly triangular forming a ‘ness’, this term having the same origin as the word ‘nose’ to which its overall shape resembles. The deposits which form Dungeness itself are mostly sands and gravels which are formed into a series of gravel ridges deposited as beach ridges which reflect earlier configurations of the coastline (figure 5). Landward of these ridges is an extensive area of lowland underlain by intertidal and marsh sediments which have been drained in historical times to form the rich arable farming area of Romney Marsh. The accretionary area of Dungeness/Romney Marsh is backed along its landward margin by a degraded former cliffline 30-40m high which stretches from Cliffend in the southwest to Hythe in the north east. This former cliffline is broken by the valleys of the Rivers Brede, Tillingham and Rother.

Evidence of past change

The evidence for past changes in the coastal environments at Dungeness is rich and varied and comes from geological, geomorphological, palaeontological, historic and archaeological studies. Consequently there are many views over the details of environmental change although there is broad consensus over the general evolution of this landform. The most conspicuous evidence for change are the series of beach ridges on the Dungeness headland which are aligned parallel to the eastern margin of the headland but are perpendicular to the beach on the southern shore reflecting the progradation of the former margin and erosion of the latter as the feature has accreted eastwards.

The long-term history of Dungeness is one of constant change. Around 6000 years ago sea levels were just recovering to approximately their present levels after the melting of the glaciers of the last Ice Age. At this time there was a broad bay stretching from Cliffend to Hythe with the Rivers Brede, Tillingham and Rother discharging directly into the bay. Cliff erosion was presumably occurring along the coast of the bay and beyond supplying sediments to the beaches and nearshore zone. Possibly as a result of sediment supplied by this erosion, bars or barrier islands began to form in the bay giving a degree of shelter to the coast such that from 4000 years ago fine sediments began to accumulate in the sheltered parts of the bay. Additional sediment may have been supplied by the rivers at this time as a result of soil erosion caused by Bronze Age clearances. By around 1700-1600 years ago the rivers were discharging into a large tidal inlet which had its mouth near Hythe. A continuous sand and gravel spit almost 30km long stretched from Fairlight in the south to the southern edge of this tidal inlet. Archaeological evidence has revealed a number of Romano-British settlements on this spit. The spit is believed to have breached at a number of locations in Saxon times as the result of sea level rise or reductions in sediment supply. By 1100AD much of the reclamation of Romney Marsh had already been completed. There followed a period of rapid erosion and accretion leading to a reorientation of the coastline of Dungeness which may in part have been due to natural forces, but to which Human interventions have undoubtedly contributed. During the 13th century severe storms caused much damage and forced settlements such as that at Old Winchelsea to relocate to higher ground. At this time Rye and Romney were important ports but the influence of Romney gradually diminished due to the accretion of shingle which blocked its entrance. In post medieval times both locations suffered from silting as the coastline reoriented. Nowhere is this coastal change more dramatic than at the mouth of the River Rother. Camber Castle was built close to the shoreline in 1538 but by 1698 shingle ridges had accumulated over 300 metres seawards. A Martello tower built at the mouth of the Rother in 1804 is now over 1 kilometre inland representing an accretion rate of approximately 5 metres per year. In order to keep the mouth of the river open and free from shingle a large groyne was built in the 1920s which has probably accelerated the accretion through northward longshore drift on its south side whilst starving the northern side of the mouth of shingle.

Impacts of past and present change

In the past large scale changes on the coastline were accepted by local communities who either exploited them by reclaiming accreting intertidal areas for use as fertile farm land as in Romney Marsh or withdrew settlements from areas threatened by erosion or flooding as in the case of Old Winchelsea. At this time there was little understanding of the potential impacts that drainage or harbour works might have on coastal change. There is no doubt that some of the more significant changes in historic times have been the result of climate or sea level changes. The area suffered badly during the 13th century, the so-called 'stormy century'. Changes in the coastline were of great political and financial importance to the maritime economy. The influence of ports for maritime trade and as naval powers could wax or wane according to local changes in sediment accretion or estuary mouth configuration. At the present time the terminal groyne at the mouth of the River Rother has a very significant impact on the orientation of the shoreline and as a result significant amounts of shingle are recycled from the Pett level shingle ridge to Cliffend every year. The southern margin of Dungeness is presently receding at between 1.1-1.5 m per year. The construction of the nuclear power stations at Dungeness in the 1960s has necessitated the recharge of the adjacent beach to counteract this recession. The power stations are built on land that has only existed for 200-400 years showing the very rapid change from accretion to erosion which now threatens modern infrastructure within a time scale which is less than the anticipated length of time that the nuclear reactors will need protection. The power stations as well as infrastructure elsewhere are also at risk from flooding which is anticipated to increase as a result of local relative sea level rise and climate change.

The dramatic coastal changes have also had their effect on habitats. The draining of Romney Marsh has reclaimed an area of intertidal habitat which would be one of the largest in the UK if it still existed. The outbuilding of the Dungeness shingle ridges has created new and rare habitats especially suited to pioneer species.

Further evidence from the geological record

Modern analogues to the accretion at Dungeness can be found in many areas of the coast of the UK where barriers have formed sheltered estuaries and embayments where fine-grained deposits have accreted. Such areas include the Norfolk Broads, North Norfolk coast, Somerset levels and the East Anglian Fens. In the fossil record such marginal marine deposits are less frequent as often they are destroyed during later stages of transgressions. A possible fossil analogue of the Dungeness beach ridges is illustrated by the Westleton Beds of Suffolk, a Pleistocene formation of well-rounded gravels and sands.

In the distant geological past deltaic deposition in England was at a scale not seen at the present day in Europe. The progradation of these deltas caused major shifts of ancient shorelines. An ancient example of rapidly accreting coastlines is provided by the Carboniferous deltas that prograded onto the tropical continental shelves that were previously sites of carbonate deposition. During the late Dinantian the Askrigg Block in North Yorkshire became subjected to the repeated advance and subsequent drowning of the Yoredale river delta which extended southwards from mountains on the area of present-day Scotland. The resulting lithologically-mixed "Yoredale" sedimentary rocks, comprising sandstones, mudstones, thin coals and typically black marine limestones, were deposited above the Great Scar Limestone Group in repeated cycles of sedimentation known as cyclothems.

The cause of the cyclothems is probably related to sea-level oscillations (see below), but some cycles also resulted from the superimposition of advancing delta lobes, whereby deltas switched position away from sites of previous delta lobes to sites where rates of subsidence were higher.

Later in the Carboniferous System (Westphalian stage, 315-305 million years ago), tropical swamps and prograding deltas covered much of what is now northern England (Figure 6). The depositional environment was a river-dominated, waterlogged coastal plain with luxuriant, freshwater marshes separated by meandering, sand-filled rivers that occasionally burst their banks to flood across the adjacent lakes or plains. The coastal plains were covered by equatorial rain forests, and the vegetation comprised a wide range of non-flowering plants such as tree ferns, horsetails and clubmosses, which provided the organic material for the formation of the coal beds for which these delta deposits are renowned.

Implications and management options for the future

There are already extensive management interventions in the Dungeness/Romney Marsh area which include hard defences against erosion and flooding, the terminal groyne at the mouth of the River Rother, and beach nourishment and recycling as well as the drainage of the low-lying areas behind the shingle ridges. Many of the environments of the Dungeness/Romney Marsh area are therefore already managed to a greater or lesser degree. The groyne at the mouth of the River Rother, which exists primarily to maintain navigation into the river, has significantly increased the accretion to the south whilst probably increasing erosion to the north of the river mouth. Its presence has certainly cut the supply of shingle to the southern shore of the headland and ultimately to beaches even further to the east. The nuclear power stations present particular management problems for the future. The southern margin of Dungeness is expected to continue to erode as shingle moves around the point of the headland and accretes on the eastern shore. The anticipated future changes of sea level and wave climate in particular may lead to this rate increasing if the present management interventions are not maintained.

The landforms of accreting coasts in general are by their very nature dynamic and often ephemeral. There are often cycles of accretion followed by erosion as the landform responds to environmental changes such as sea level, sediment supply or climate change and to the interventions of Man. These cycles are often remarkably rapid and need to be understood within the context of any management time frame. The dynamic nature of accretionary coasts make them rare and unusual habitats which attract a specialised group of species of plants and animals which are adapted to this often harsh environment. In the face of predicted sea level rise and climate change it is likely that accretionary landforms will continue to respond to these forces perhaps in an even more rapid way and in directions that may not always suit Man's ambitions.

At the present time there is a lot of discussion about using natural accretional features as "soft" engineering solutions for coastal protection. Saltmarsh, sand dunes and beaches all provide a natural defence against flooding by the sea, and can offer some protection to sea cliffs against wave attack. The rough substrate provided by saltmarsh vegetation is particularly effective in reducing wave energy. For much of the twentieth century, reclamation of saltmarsh for farmland was a common practice and "hard" engineered coastal defences were often preferred as a means of protecting this reclaimed land. In recent years, a better understanding of coastal sediment budgets and the availability of fine sediment (mud) needed for saltmarsh growth has led to the concept of re-establishing saltmarsh as a natural form of coastal protection as part of coastal realignment schemes, for example in the River Blackwater in Essex. Because the accretion of saltmarsh can keep pace with a gradually rising sea level, providing sediment sources are maintained, this form of "soft" coastal defence could also remain effective over a longer time period than "hard" defences. Beaches have also been replenished, particularly along the Lincolnshire, Sussex and Hampshire coasts, to protect against sea flooding and foreshore erosion as well as helping to maintain a recreational facility. English Nature is working to achieve this shift in practice from coastal defence to coastal management where use of natural coastal defence functions would help to recreate coastal habitats and to preserve biodiversity.

2.2 EVOLVING RIVER SYSTEMS

2.2.1 Floodplains do flood

Introduction

Natural floodplains in the UK are inundated on average once every 1.6 years, but some catchments with extensive built-up areas flood on average more than once every winter. A river floodplain is therefore a highly appropriate scientific name for the valley floor which provides a natural storage area or conduit for water during times of exceptionally high river flows, when the capacity of the main river channel is exceeded and the ground underlying the floodplain is saturated. This description carries an obvious hazard connotation so it is clearly important to define the edges of floodplains. Presently, however, there is a lack of consensus over what is meant by a ‘floodplain’, with terms such as ‘flooding limit’ often used synonymously. Thus the government’s paper ‘Development and Flood Risk’ (Planning and Policy Guidance Note No.25) states that the limits of floodplains cannot be defined precisely and that floodplains ‘…are often delineated by the estimated peak water level of an appropriate flooding event’ (e.g. a flood with a 1% annual exceedance limit, or 1 in 100-year return-period). The problem with this usage is that any number of exceedance limits can be arbitrarily chosen, resulting in many separate ‘floodplains’ existing within a single river valley!

Floodplains can be portrayed in a highly visual manner, on geological maps. On these maps geologists determine the limits of floodplains not on the basis of statistical probabilities, but by treating floodplains as natural landforms. The floodplain boundaries are shown as a line on the map corresponding to a change in slope gradient, observed in the field, intervening between essentially flat ground, representing the depositional surface of the modern floodplain alluvium, and gently sloping ground on either side, which could be the bedrock or earlier 'terrace' deposits bordering the floodplain.

Purpose of case study

The Trent valley to the east of Nottingham illustrates well the many facets of a typical floodplain in lowland England and the risk of flooding. The Trent floodplain contains much fertile, flat-lying ground that is favourable for arable cultivation, but has also seen the encroachment of urban sprawl and ‘out of sight’ industrial developments. In years of normal rainfall distribution the floodplain surface is largely dry. Historical records nevertheless show that the valley has experienced repeated flooding, a lesson that was forcefully brought home by the floods of November 2000. When valley development is traced back through Quaternary time it is apparent that climate has played a large part in moulding floodplain morphology. It follows that future climate change will be a major factor not only controlling how floodplains develop, but how humans can best utilise them.

Description of the Trent Valley case study area

The principal geomorphological elements of the study area (Figure 7) are the c. 3 km wide floodplain that is cut into red Triassic mudstone bedrock, and the main river channel, of 100 m average width, which meanders across the floodplain. It is the interrelationship between these two features, and in particular the process of channel migration, that has generated the modern topography of the Trent valley floor. The floodplain sediments originated from further upstream by overbank flooding or on the inner bends of meander channels. Meander migration has undoubtedly occurred at times of high flow over the past millennium, but in recent decades only two hydrodynamic regimes have been witnessed. At 'normal' times, of average or below average rainfall distribution, water levels in the main channel are up to 2 m below the surrounding floodplain surface and the floodplain remains dry, undergoing modification only as a result of soil formation and human activities such as ploughing and construction. A radically different regime prevails at times of abnormally high water supply, as was demonstrated by the November 2000, 1-in-65 year recurrence period flood event when the peak flow rate in the main channel was 20 times in excess of that in normal years. During this event the riverbanks were locally scoured, the river overflowed its banks and large parts of the floodplain were inundated by sluggishly-flowing or locally ponded, silt and sewage-laden water (Figure 8). The high groundwater tables prevailing on the floodplain caused inundations behind obstacles, such as railway embankments, which otherwise would have protected against surface overflows from the main channel.

Evidence of past change

The geological history of the Trent floodplain poses a salutary lesson to those who seek to continue to develop it for human occupation. The valley it occupies actually dates from the end of the Anglian glaciation, about 450 000 years ago, and has been widened and deepend by five major episodes of floodplain construction, abandonment and incision. Driving this complex process were external factors such as progressive uplift of the region, fluctuating sea levels and the extreme oscillations of climate that have characterised the late Quaternary period. River terraces testify to the existence of former floodplain levels of the Trent that originally formed sandy braidplains. Dating of these deposits shows that they were formed at times of high water supply during the cold, periglacial climatic regimes of the late Quaternary.

The modern regime of the Trent channel and its surrounding floodplain was initiated in early Holocene times, about 10 000 years ago, after the Devensian ice sheets had disappeared from the Pennine uplands. It is typical of lowland river systems prevailing during a relatively mild and dry climatic regime, when sediment supply is low and earlier floodplain deposits, such as the Holme Pierrepont terrace (Figure 7), are being reworked by the process of channel migration. High flow velocities, and consequent widespread flooding, would have accelerated this process although there has been no discernable change in channel configuration since the earliest Ordnance Survey maps were published in the mid to late nineteenth century

Impacts of past and present change

The geology of the Trent floodplain clearly indicates a dynamic river system that is in a constant state of change. If today's climate were to persist, it is possible that the rate of natural change on the floodplain would be relatively slow. Current forecasts, however, are for winters to be 30 per cent wetter by 2080, than they are now, meaning that that severe flooding will be a more regular occurrence and the rate of migration of river meanders will also probably increase. Such predictions place many existing dwellings, industries and communication routes on the floodplain at considerable risk, and suggest that the scenarios of the November 2000, ‘65-year’ flood (Figure 8) will be witnessed much more frequently.

Implications and management options for the future

The new guidelines on flood risk, issued in the government’s Planning and Policy Guidance Note 25, clearly state that susceptibility to flooding is a major planning consideration and that planning decisions should ‘avoid such risk where possible and manage it elsewhere’. The implication is that any new development must be accompanied by a viable flood risk management strategy, and there is a requirement on the scientific community to deliver the information on which such planning decisions are to be based.

The severe floods of the past few years have stimulated a ferment of research into the scientific and societal aspects of floodplains in the UK, with organisations such as the Department for the Environment, Food and Rural Affairs (DEFRA) and the Environment Agency playing a leading role in developing strategies to mitigate the effects of flooding. The Environment Agency’s *River Trent Strategy* document (unpublished draft, June 2002), for instance, lists no less than 19 options for flood management. They range from direct intervention, such as the construction of flood banks (particularly in existing urban areas), the re-routing of the main channel and excavation of flood reservoirs, to more natural measures such as improved farming practices, afforestation of the catchments, and reversion to natural floodplain environments. The latter would involve the removal of artificial embankments allowing water to more readily occupy the floodplain, but must be accompanied by improvements in flood warning and awareness, local flood protection measures and possibly compensation to properties affected. English Nature supports these moves, and moreover is campaigning for floodplain restoration and creation of new wildlife habitats to help deliver biodiversity targets. In a pragmatic and holistic approach to flood management many of these measures should probably be used in combination, the mix of options being tailored to environmental constraints as well as those of society in different sectors of the floodplain.

With climate change impending, the challenge for environmental geoscientists and engineers is to clarify the history, structure and physical properties of floodplains and their catchments, to define floodplain boundaries and accurately assess flood risk limits. This information will underpin planning decisions, policies and guidelines for areas at risk from flooding, but the main aim should be to manage floodplains in a sustainable manner in harmony with their natural functions and environments.

2.2.2 A changing river course

Introduction

The evolution of river systems has received enormous attention from environmental scientists. Changes in the course of a river are effected either by downcutting, the manner in which channels erode underlying rocks or sediments, by the deposition of sediment load and by the lateral migration of a channel. Each of these processes is, in turn, influenced by changes in discharge and sediment load. Downcutting towards a base level, commonly sea level, is an early stage in the development of a river system, and river terraces are often generated on the higher, abandoned parts of the floodplain. Deposition is a feature more commonly associated with the lower reaches of rivers forming conspicuous alluvial plains and floodplains. The lateral shifting of channel courses is a tendency in all rivers where not constrained by solid rock outcrops. Lateral shifting can be very rapid in braided channel courses, but the more gradual lateral shifting caused by the process of meandering is most conspicuous at the present day and can be preserved in the rock record. Meandering is the tendency for any naturally occurring, unconstrained, river channel to develop a curved course in plan view. Uneven river banks and channel floors create eddy currents within the river flow, which tend to enlarge existing irregularities and lead to further bank erosion. Continued erosion enlarges the concave outer banks. On inner channel margin the slower river flow deposits sandy sediment, 'cannibalised' from erosion farther upstream, in the form of successive arcuate point bars, which can, for example, be seen in the Trent valley (Figure 7).

Purpose of the example

In order to demonstrate that rivers can shift their course significantly, and that a river valley is a dynamic environment evolving over time, we have to look no further than a river as familiar as the Thames and its history over the past two million years. The much coarser sediment load of the ancestral River Thames, and by implication much higher river flows along the Thames in the early Quaternary, show the impact of climate change, in this case caused by the onset of glaciation, on the physical character of a river.

Description of case study area

The region influenced by the course of the Thames over the Quaternary stretches from the present Thames river basin to the Chilterns to the north Norfolk coast. There is a high demand for sand and gravel aggregates in south-east England, and as a consequence widespread quarrying of coarse-grained Quaternary sediments has occurred over the past few decades. The best quality aggregates, which occur throughout the Thames Valley and across parts of East Anglia, were deposited within river courses of an ancestral Thames drainage system or as glacial outwash deposits. These Quaternary river deposits not only have an economic importance, but also provide an invaluable record of the changing environment of southern England leading up to the onset of the major Anglian glaciation. Many of the gravel quarries have SSSI status.

Evidence of past change

Geological maps of the distribution of the largest sand and gravel deposits both onshore and offshore south-east England show some startling features. A belt of Kesgrave Sands and Gravels) is widely exposed in Essex and south Suffolk, and records that the ancestral River Thames during the early Quaternary had a very different course compared to the present day. It drained into the North Sea at various locations in the vicinity of Ipswich, with parts of the outer estuary extending to the Norfolk coast (Figure 9). Maps of the seabed sediments show extensive river gravel sheets in the eastern English Channel. These sea floor gravel sheets date from a later Quaternary stage when a blocking ice sheet in the southern North Sea, or an exposed land barrier at times of lower sea level, redirected drainage from the Thames and the northwest European rivers down the English Channel.

The coarse-grained nature of the ancestral River Thames sediments (Figure 10) is in complete contrast to the muddy Thames estuary that we see at the present day. Grain size is directly related to the energy of river flow, and the predominantly gravel bars and coarse-grained channel deposits of the Kesgrave Sands and Gravels are characteristic of high discharge braided river deposits. Medium- and fine-grained sands are also present in the deposits, reflecting periods of lower discharge and the formation of small dunes and ripples migrating over the gravel bars. Braided gravel bed rivers are often found at the present day at high latitudes in snow-capped mountainous regions where spring meltwaters are capable of carrying heavy sediment loads. By analogy, the generally coarse-grained ancestral Thames sediments with their indications of variable flow regimes are the product of seasonal variations in the flow of meltwaters draining from the margins of an ice sheet. Deposits of the lowest reaches of the ancestral Thames, seen in Norfolk, show tidal influences in their style of bedding, representing outer estuary deposits. The deposits of the ancestral River Thames also preserve abundant evidence of fluctuating climatic conditions. Ice-wedge casts are frequently recorded within the Kesgrave Sands and Gravels indicating a periglacial climate at the time of deposition. However, pollen obtained from ancient soils on abandoned river terraces at the top of the deposits indicates the onset of an interglacial and a return to temperate climatic conditions coincided with the end of gravel bed river deposition.

Impacts of past and present change

The river Thames has changed its course on numerous occasions in the past and has the potential to do so again in the future. One of the obvious trigger mechanisms would be a change in sea level. Evidence from the past shows that the Thames adjusted to lower sea levels, leaving its oldest deposits on higher ground in terraces. A future rise in sea level, without human intervention, would lead to flooding of the estuary margins and siltation of the main channel, with channel avulsion possible in the outer estuary. Flooding of central London is a real potential risk, though one which has been lessened by the presence of the Thames barrier to protect against high tides and storm surges, the construction of which was completed in 1984. Upgrading of the Thames barrier will probably be a necessary response to this higher flooding risk.

Further evidence from the geological record

The Middle Jurassic rock sequence displayed in the cliffs of the North Yorkshire coast shows channelised sandstone beds and clear evidence of lateral migration of the river channels. The sandstones stand out as hard, rusty-brown beds that form resistant ledges and platforms all along the coast. When traced laterally, the base of many of these sandstone beds undulate markedly and sometimes can be seen to cut down into underlying beds. These erosion surfaces, formed when the sandstones were first deposited, tell us that the original sands were being carried along by strong currents, powerful enough to cut channels into the still soft underlying sediments. Channelled beds of this type range in scale from a few tens of centimetres to several metres in magnitude. Clearly, the biggest channels were cut by very powerful currents. Such channelled surfaces dominate the succession along the cliffs (Figure 11). Within the thicker sandstone beds it is also evident that there are many other surfaces visible, many are steeply inclined, first in one direction and then switching to the opposite direction. They tell us that the beds of sand were being deposited quite rapidly, not on the floor of the channel as we might first expect, but on the inclined sides of the channel. If we look at a modern river channel we find that this type of inclined structure occurs wherever a river bends or meanders. As a river winds along its course the sediment load which it invariably carries, is gradually dumped along the inner bends of the meanders where the energy of the water flow, and therefore its ability to carry sediment, is at its weakest. Conversely on the outer part of the bends the energy of the river is at its greatest and erosion of the banks occurs. As the outer bends are so strongly erosive the channel margins are rarely preserved in the sedimentary record. The change in direction of the bedding planes in the sandstones tell us that the Yorkshire coast was the site of some extensive areas of meandering channels.

Implications and management options for the future

Future climate change could lead to new changes to the river flow regimes. In many cases this means a higher discharge and therefore sediment load due to heavier rainfall. In the case of the Thames, the flooding seen in the vicinity of Maidenhead in 2000 may become more frequent in the future.

Lateral migration of the Thames channel is largely constrained by flood protection works in central London and other urban centres along its course, and it would seem inconceivable that these defences would not be maintained in the future. The natural tendency of the channel course to meander is most likely to occur in the middle and upper parts of the Thames catchment, beyond the limit of tidal influence at Teddington. As with all unconstrained lowland river courses in England, erosion will occur in the future on the outer and downstream sides of meander bends, even if signs of outer bank erosion are not apparent at the present day. It would therefore be sensible if preference was given to further riverside developments on the inner banks of large meanders, and to discourage development, or at least make developers aware of the need to protect against river erosion, on outer meander bend sites. This is not withstanding the natural flooding risk on all floodplain development sites and that the inner bends close to the channel are lowest and, where undefended, will be first to flood.

English Nature is working towards encouraging catchment-scale flood strategies, where areas of the floodplain susceptible to flooding and erosion are deemed inappropriate sites for development, and new wildlife habitats are created at the expense of agricultural land. Floodplains should be managed in ways that work with nature wherever possible.

2.3 UNSTABLE GROUND

2.3.1 MOVING SLOPES

Introduction

Soil and rock talus has a natural tendency to gradually move down-slope under gravity, often by creep, rockfalls, debris flows or mud flows depending on the material involved. However, rapid down-slope movements by landslides are most spectacular and can move large amounts of material in single events. England does not suffer from catastrophic landslides on the scale witnessed in actively growing mountain regions of the world, though it does contain over 10,000 relict inland landslides dating mainly from around the last ice age when the climate was generally wetter and periglacial conditions were widespread. Some of these landslides have become re-activated either because of unusually high rainfall or occasionally by engineering activity. Such is the case with Mam Tor in Derbyshire, one of Britain’s largest inland landslides. Active erosion of the coast ensures a continued cycle of landsliding of sea cliffs, and the complex of landslides on the coast at Charmouth (Dorset) are among the largest coastal landslides in Britain. Intermittent landslide activity can disrupt roads, services, properties, and ancient monuments, incurring considerable cost.

Purpose of case examples

Landslides represent a hazard to human activities, which in common with many other geological hazards, is difficult to quantify and predict. A key process in the case of inland landslides, the great majority of which are pre-existing, is that of re-activation either by engineering activity or by unusual rainfall events. However, on the coast fresh landslides predominate, and are more common due to the continuous process of landslide debris removal by coastal erosion. In order to quantify the hazard associated with landslides their mechanisms need to be understood and, where necessary, movements and other parameters need to be monitored.

Description of study sites

Mam Tor, Derbyshire

This approximately 4,000 year-old feature near Castleton, in the northern Derbyshire Peak District, cobers 0.5 km^2 with a fall of 250 m, on an overall slope of 30^o and a maximum thickness of 40 m. It has a distinctively high and steep backscarp which has cut away the corner of the hilltop Iron Age fort. The rocks are mudstones and sandstones of the Namurian Mam Tor Beds and the Edale Shales. Landslide movement has been more or less continuous over the last century, and has totally disrupted the A625 Trans-Pennine trunk road, necessitating a major diversion in 1979. The landslide has a complex structure of slide blocks, debris flows, solifluction lobes, and screes (Figure 12). The landslide moves about 0.25 m annually, mainly in the central section, but after heavy rainfall the amount of movement increases markedly. Large landslides are also found nearby on the Edale flank of the watershed.

Charmouth, Dorset

The Black Venn landslide complex at Charmouth, extending about 4 kms westward from the town to Lyme Regis, occurs within Lias, Gault and Upper Greensand rocks that are dominated by weak mudrocks and sands. The principal mechanisms of landsliding are rotational slumps and mudflows, the former reaching a thickness of 35 m. A feature of the complex is the presence of an 'undercliff' formed on a bench of more resistant mudstone. In December 2000 a major re-activation of the undercliff took place at Cain's Folly, Stonebarrow Hill to the east of Charmouth releasing hundreds of thousands of tons of material onto the beach (Figure 13). The complex landslide between Charmouth and Lyme Regis, to the west, is known as Black Ven. This is up to 135 m high and has undergone 3 major phases of activity during the last century. Major engineering works are underway by West Dorset District Council to remediate the effects of landsliding.

Evidence of past change

The history of re-activation of inland landslides, and of coastal erosion and sea-cliff recession, go back through several centuries, if only anecdotally. Archaeological records have played a key role in England as elsewhere, for example the relationship between the landslide at Mam Tor and the Iron Age hilltop fort, or the historic loss of coastal settlements to erosion. Scientific investigation over the last 50 years has revealed the age and cycles of activity of landslides. The geological, mechanical, and environmental processes that determine this activity are now better understood and permit remedial measures to be designed and applied to reduce the hazard.

Impacts of past and present change

The impacts of inland landslide re-activation and coastal cliff recession are widespread. Disruption is not confined to structural damage and personal injury, but also includes severance of transport routes and services, loss of access, and sterilisation and devaluation of land. Repairs are often applied repeatedly, in some cases finally requiring major engineering works, relocation of facilities, and route diversions. Coastal cliff recession provides relentless problems and expense for local authorities particularly in residential, tourist, and industrial areas. Planning is hampered by a general lack of local scientific data and behavioural models to allow predictions of coastal recession to be made.

Further evidence from the geological record

Slope movements have occurred throughout geological time, and the geological record is full of examples of slumping of beds, often related to tectonic movements. For instance, there is abundant evidence of slumping and debris flows within limestone beds that are found within the Dinantian Worston Shale Group, exposed on the Bowland Fells of Lancashire. During the Dinantian in Lancashire and West Yorkshire, sea-level fluctuations and tectonism caused limestone debris to be shed from the shallow water carbonate platform into the adjacent Craven Basin, with the rapid emplacement of limestone debris causing slumping of beds on the basin margin.

Implications and management options for the future

Much can be learned about the likely behaviour of landslides from a study of the history of the processes and their relationship to environmental factors, such as rainfall. A recurring theme is the reactivation of old landslides, of which many instances occur, for example on the M6 descent to the Cheshire Plain and on the Sevenoaks bypass. For this reason it is important to preserve, where possible, the evidence of past activity. Some geological SSSI’s include landslides, such as those at Charmouth and Mam Tor.

The classification of coastlines and of landforms in terms of stability and hazard for planning purposes is a key activity which requires scientific and engineering knowledge as well as data specific to the local conditions. These data are usually costly to obtain, whether on the ground or remotely by aircraft or satellite. However, ignorance of the issues may also prove costly in the medium and long term. Increasingly, coastal industrial developments, such as offshore windfarms, pipelines and reclamation for airports or harbours, require access to engineering data, and estimation of hazards, ecological impacts, and longevity. Their relationship to geology and geological processes is fundamental.

The British Geological Survey thus holds a register of reported UK landslides which can be consulted by potential developers. It is the intention of BGS to provide an on-line hazards database which planners could consult if they suspect that their development site is at risk of ground movement.

2.3.2 Subsidence and the development of cave systems

Introduction

Areas of limestone or rocks containing evaporite minerals such as gypsum, anhydrite or halite (rock salt), which were formed by concentration through evaporation, are prone to dissolution and subsidence (Figure 14). Such areas form special landscape types, the most common of which are the karst limestone areas with their cave systems, limestone pavements and unique floras. Limestone dissolves moderately quickly, but gypsum, the raw material for plaster, and halite dissolve between one hundred to ten thousand times quicker than limestone. Because these minerals dissolve so quickly, they affect the countryside on both a human and a geological time-scale. Their removal causes subsidence and the development of a buried karstic landscape. This is not as obvious as the limestone karst, but similarly it has a unique environment and floras. Problems encountered by the city of Ripon (see below) demonstrate the hazards of building on rocks that suffer solution subsidence.

Cave systems are especially important, not only for their intrinsic beauty, but because they represent natural ‘time capsules’, protected from surface weathering, erosion and biological disturbance. Most have developed over the last few hundred thousand years, although some caves are much older. They often contain a variety of geomorphological features and deposits, which can provide information about past climates, vegetation history, past water movements and landscape change.

In particular, stalagmites and stalactites ('speleothems') are important repositories of data relating to past climate change. Locked up in their crystal lattice are isotopic clues to the changing environment. Over time, the composition of each layer of calcite that precipitates sets "in-stone" information about the drip-water that fed it and hence the climate and vegetation of the land surface above. As speleothem deposits can be accurately dated by isotopic methods, this information can be put into its chronological context. The timescales of the palaeo-environmental record provided by the sediment and speleothem deposits is far in excess of those commonly preserved in surface environments.

Speleothem growth is switched on and off by the changing climate. During cold glacial periods, groundwater flow is restricted and speleothem deposits don't form. During warm and wet periods, speleothem growth commences again. By dating these deposits, it is possible to constrain the timing of the interglacial and glacial cycles. An example of a slabbed stalagmite deposit is shown in Figure 15.

Caves also provide important natural habitats for a range of species, including bat roosts for the endangered Greater and Lesser Horseshoe bats. Limestone pavements, often found on the surface above cave systems, are also important habitats, and are very fragile landscapes. They have evolved over the past 15,000 years, after being cleared of regolith by the Devensian ice sheet, but can be easily destroyed by quarrying for ornamental stone. Excellent examples occur at Hutton Roof Crags SSSI in Lancashire, and the Malham area in North Yorkshire.

Purpose of case studies

The Mendip karst (Cheddar SSSI) shows that sudden catastrophic flood events can dramatically change an underground cave system within a matter of hours. Just as high rainfall can affect a surface river course, high rainfall can cause flooding and morphological changes to cave systems. The case study is also an example of the negative impact of human interference on the natural environment. Quarrying has destroyed caves and the karst landscape at a greater rate than it is being created. In the eastern Mendips, sub-water table quarrying has radically altered the groundwater system. Some dolines or sinkholes are also being filled with tipped refuse, which will also affect the chemistry of the percolating groundwaters.

Description of case study area

The Mendips contain some of the best studied cave systems in England, and recent changes to the cave system are well documented. During storms and severe flooding of the caves on July 10th 1968, surface collapses, mudflows and the erosion of previously stable sediment fills occurred (Figure 16). Two caves particularly affected were GB Cavern and Swildon's Hole. A large mudflow within GB Cavern resulted from the collapse of a choke and the creation of a large surface doline. The sediment deposited from this mudflow has been gradually flushed through the cave system over the past thirty years. In Swildon's Hole, the erosion of cave sediment and a stalagmite-blocked passage occurred in a matter of hours, altering the course of the underground stream. Elsewhere in the vicinity, the same flood event caused numerous surface collapses, some up to 15m deep, floodwaters raged down Cheddar Gorge ripping holes in the road up to 6 m deep and many dry valleys became rivers and water again flowed through some relict caves.

Evidence of past change

Detailed studies and dating of cave sediments and speleothem deposits in the Charterhouse, Priddy and Chedder Gorge Caves (all SSSIs), identify many periods of cold climate extending back over the last 900,000 years. Equivalent surface deposits have long since been eroded or destroyed by weathering. Dating of the cave deposits, and determining former water-tables levels within the caves, enables environmental scientists to determine rates of landscape evolution, such as the rate of incision of Chedder Gorge.

Impacts of past and present change

Ground instability is the most obvious manifestation of continued cave development. The largest and most spectacular dolines occur where thin permeable sediments overlie karstic rocks. In Dorset, many large dolines occur where permeable Palaeogene sand with clay overlies the Chalk. The most spectacular is the Cull-Peppers Dish SSSI, which is a large doline 21 m deep and 80 m in diameter. New dolines continue to form and several small collapses have been recorded in recent years, one disturbing a Bronze age burial site.

Dolines also occur where surface streams disappear underground, and their location can change from year to year. This is particularly apparent at the Water End Swallow Holes SSSI, near Potter's Bar, Hertfordshire, where the Mimmshall Brook sinks into the Chalk. Here, new dolines appear at irregular intervals and the surface drainage may be noticeably modified after a major flood. In areas of Permian rocks where gypsum solution can be a problem, subsidence hollows can become water-filled and subsequently colonised by a unique pond flora (Figure 16). Although floods and heavy rain are prime triggers for ground instability and can rapidly alter cave and karst landscapes, on other occasions cavities can suddenly collapse without prior warning. It is clearly important to undertake thorough site investigations prior to construction works in areas of solution-prone bedrock.

Further evidence from the geological record

The Malham area of North Yorkshire is also famous for its karst scenery of dry waterfalls as at Malham Cove, for its limestone pavements (Figure 17), and extensive underground cave systems. Well developed depositional features such as the mounds of glacially-shaped till known as drumlins are also present in the Craven lowlands, together with outwash sands and gravels in the major river valleys, and kame and esker landforms near Malham Tarn. Scree slopes occur along the foot of the dry valleys, with no evidence for their formation at the present day. Also, sandstone erratics famously rest on limestone pillars above a limestone pavement at Norber in Crummack Dale. All these features are essentially Quaternary in origin, and reflect the profound modification of the landscape that occurred during the last, Devensian glaciation from about 26,000 to 10,000 years ago.

Much of the karst topography developed after ice scoured away the soil covering and exposed bare limestone to acidic rainwater attack. Initially till and fine sediment deposited by the ice within joints and cavities in the limestone would have impeded the percolation of water through the limestone. As the ice sheets began to melt and recede, meltwaters in channels below the ice were for a time able to flow across the bare limestone surfaces, cutting the dry valleys and forming waterfalls on fault scarps. Good examples include Watlowes dry valley, which terminates at Malham Cove, and the channel now occupied by Gordale Beck. Such valley floor profiles show occasional humps in a generally falling height along their length, indicating some uphill flow of meltwater under hydrostatic pressure which is consistent with their formation below an ice sheet.

North Yorkshire cave deposits also reveal critical information on human and animal occupation of the northern Pennines during the Quaternary. Victoria Cave, in limestones near Settle, has revealed an assemblage of mammalian bones including straight-tusked elephant, rhinoceros, hippopotamus and hyaena dating from the last (Ispwichian) interglacial from deposits in the lower parts of the cave. Higher in the cave, the bones of arctic fox and grizzly bear, dating from the last (Devensian) glacial period were found. Neolithic and Romano-British pottery and human remains have been recovered from other caves in the area.

The impacts of Quaternary climate change on these ancient limestone sequences also serves as a warning of the dramatic landscape changes that would occur if England was affected by another glaciation.

Implications and management options for the future

Man's activities are another major cause of ground instability. Karst landscapes are dynamic features. Cave systems provide efficient drainage networks, enabling the rapid transport of water and pollution from dolines to springs, with little or no contaminant attenuation. Tipping of refuse in dolines may seem a good way to level a hole in the ground, but it potentially contaminates a public water supply many kilometres away. Altering these karstic drainage networks by quarrying, over-abstraction of groundwater and blocking dolines, will all affect the karstic hydrological system, often with unforeseen consequences, and therefore should be restricted by planning authorities.

Naturally stable dolines and sediment filled 'pipes' in Chalk can be destabilised by inadequate drainage, poorly designed soakaways and construction work. For instance, the flushing of sediment infilled dolines and pipes, in particular above old chalk mine workings, is a common cause of collapse. Dissolution pipes and cavities in the Chalk can be easily missed by conventional drilling techniques, so it is recommended that geophysical methods are used to locate dissolution features in site investigation work for buildings in Chalk areas.

The problems caused by karst landscapes are perhaps most evident in areas of evaporite-rich rocks. For instance, in the city of Ripon, North Yorkshire, where subsidence and difficult ground conditions for development are caused by gypsum dissolution. Some houses recently built on unstable ground have suffered severely from subsidence cracking, and large solution cavities have opened up in gardens (Figure 18). The understanding of the causes and likely rates of collapse have helped guide development in the area. This could not have been done without the study of the natural exposures and subsidence features in the vicinity. The buried karstic landscape is controlled by rapid underground water flow and gypsum dissolution, conditions that also permit the rapid migration of contaminants from the land surface to the subsurface and out to springs along the local rivers. In areas of evaporite-bearing bedrock such as at Ripon it is essential to protect the groundwater from pollution both to conserve these environments and to protect the local aquifer. It is also essential to develop the aquifer in a controlled manner because over extraction itself can enhance the amount of dissolution and cause collapse by inducing fluctuations in the local water table.

Being more aware of karst landscapes, cave systems and the processes that form and continue to shape them, will help and preserve the fragile karst landscape and the valuable resources it contains, and avoid potential geohazards. It is the intention of BGS to provide an on-line hazards database which would include karst hazards. This would provide planners with a first point of call if a ground hazard is suspected.

3 Rapid / catastrophic events

3.1 THE INFLUENCE OF GLACIATIONS

3.1.1 Changing climate

Introduction

The encroachment of ice masses over land areas has left a legacy of distinct geomorphological features and sedimentary deposits that prove that northern and central England have been subjected to repeated glacial pulses in the last two million years, and therefore repeated cycles of cold glacial and warmer interglacial temperatures. Deposits of till, mostly an unsorted mixture of rock fragments and rock flour deposited by ice sheets, are widely distributed over northern and central England. Diagnostic rock types within the tills can be used to indicate ice transport paths. For instance, fragments of Shap granite sourced from Cumbria and rhomb porphyry mostly sourced from Scandanavia. Equally diagnostic of past glacial episodes are landforms of both depositional and erosional origin that developed in proximity to ice sheets and which can still shape the surface topography of many landscapes at the present day. Depositional landforms such as drumlins, kame terraces, eskers and moraines form hummocks and ridges in a landscape, and are often associated with large boulders known as erratics derived by ice transport from often distant sources. Sheets of water-lain sand and gravels, laid down in outwash plains or sandurs, can also be deposited in ice margin areas. Erosional features such as U-shaped valleys and rock striations are typically found in upland areas of northern Britain. Natural English lakes can trace their origin back to periods of glacial scouring, and glacial deposition forming natural dams within valleys.

Purpose of case study

Despite the current trend of global warming, most environmental scientists believe that Britain is currently within an interglacial period and that a return to glacial conditions at some time is inevitable. Studies of patterns of Quaternary ice advances and retreats based on changes in the Earth's orbit (Milankovitch cycles) indicate the maximum of the next glaciation will occur in about 60,000 to 70,000 years time. The geological record can provide evidence of the magnitude of natural climatic variations, and of the duration of periods of climatic stability. The study of glacial sediments reveals the range of physical impacts and landscape changes resulting from the advance of an ice sheet, and some of the largest exposures of these sediments are found on the north Norfolk coast.

Description of case study area

The cliffs between Happisburgh and Sheringham in northeast Norfolk and the adjacent hinterland provide a detailed record of ice margin environments mainly dating back to the Anglian glaciation approximately 430,000 to 480,000 years ago. Ice marginal geomorphological features relating to the Devensian or last glaciation, which reached its maximum extent 18,000 years ago, occur mainly in northwest Norfolk (Bridges, 1998), and it is thought that the Devensian ice sheet did not reach the northeast Norfolk coast. The attractive landscape seen today, favoured by bird watchers and ramblers, hides a dramatic past of ice sheets scraping across a barren land surface, then depositing ice-transported detritus in piles or in meltwater-lain courses as the ice melted and retreated northwards.

The cliffs between Overstrand and Sidestrand show a succession of silty tills, deposited below ice sheets, interbedded with lake deposits, recording a fluctuating ice margin with ponding of meltwaters during periodic retreat of the ice front. The lake deposits contain dropstone pebbles, deposited from melting blocks of ice floating on the lake, and are overlain by sands which probably accumulated in deltas at the margins of the lakes. The cliffs are well known for their exposures of contorted tills, the folding and faulting of which was probably caused by pressures from the re-advance of ice sheets. The lake deposits have also been subjected to some subglacial deformation, distorting the primary lamination. Perhaps most dramatic of all are large chalk blocks, some over 50 m long, which have been thrust up from nearby bedrock by the force of the overriding ice sheet (Figure 19). These chalk blocks are largely undeformed, preserving their original bedding surfaces with aligned flints, suggesting probable transportation in a frozen state. These blocks demonstrate the sheer power of a moving ice sheet. If Britain moves into another ice age, it is not only the falling temperature that we should be worried about, but all the other impacts associated with ice sheets as well. The final retreat of the ice sheets after the end of each glacial maxima initially heralded a return to periglacial conditions, as attested by frost wedge casts in the cliffs, before warmer environments returned.

Evidence of past change

Quaternary shallow marine and freshwater mixed deposits, including peats, which are older than the Anglian glaciation, are intermittently exposed near the base of the Norfolk cliffs. There is a wealth of evidence from pollen trapped in these sediments to document transitions from periglacial cold environments to interglacial temperate periods (Figure 20).Warmer temperatures prevailed before the Anglian glaciation during the Pastonian and Cromerian interglacials when Norfolk was covered by a mixed deciduous woodland. The much studied peat bed of the Cromer Forest Bed Formation is judged to have formed at some time between 700,000 and 500,000 years ago on the basis of mammalian remains. Dating of these sediments is too imprecise to appreciate the duration of these Quaternary climate change events in East Anglia, but the evidence from the pollen of frequent climatic changes is nevertheleess of great scientific value.

Impacts of past and present change

During a glaciation the appearance of North Norfolk would not be dissimilar to ice margin areas seen in Iceland at the present day, with ponded lakes, moraines and frequent snowstorms, with sparse vegetation and wildlife. Human habitation in north Norfolk at these times would have been virtually impossible. When our ancestors migrated into North Norfolk across the European land bridge as the glaciers receded, they would have found a tundra landscape with frozen ground being replaced by pine forests and deciduous woodland as temperatures increased at the start of an interglacial. The present trend for global warming masks the risk of a sudden return to cooler conditions, for example if the Gulf Stream was weakened by the additions of freshwater from Arctic ice melting, which could leave Norfolk with a climate more typical of Siberia within just a few years.

Further evidence from the geological record

The rock record is full of sedimentary rocks deposited under different climatic conditions, from the Permo-Triassic desert and saline lake sandstones and mudstones (Figure 21) to some of the deep water submarine slide deposits found in the Carboniferous rocks of northern England.

Implications and management options for the future

The northeast Norfolk cliff exposures preserve an invaluable record of Quaternary climate change at the margins of an ice sheet. The cliffs in Norfolk are retreating at one of the fastest rates in England, often by several metres per year, exceeded only by the till cliffs of Holderness. Seawalls and groynes protect all the main coastal towns and some adjoining sections of cliff. The remaining unprotected cliffs provide the largest exposed sequence of these ice margin glacial deposits in Norfolk. It is important that some exposures remain accessible for study, because the continuous exposure of new sections over time adds to our knowledge of Quaternary sediments. Moreover, the cliffs provide an important sediment supply to the beaches and nearshore zone, recently as far as Great Yarmouth. Until recently a southerly littoral drift of sediment helped to support the continued presence of the banks and shoals offshore from Winterton, but the supply is now cut off by the emplacement of reefs at Sea Palling.

How can we plan for and manage climate change?

3.1.2 Changing sea-levels

Introduction

The growth and decay of ice sheets in high latitudes controls world sea levels. The Quaternary geological record provides evidence that sea levels have often been much lower than at the present day. During glacial maxima, the sea level was up to 130 m below its present position because of the very large amounts of water locked in ice sheets, and England was linked to Europe by a land bridge. After the last ice age this land bridge persisted until about 9000 years ago. Our ancestors were able to move freely to southern England from what is now the European mainland, but the north of England would have been inaccessible while covered by ice.

The relative position of sea level and the land is further complicated by the issue of isostacy, whereby land areas are depressed under the weight of an ice sheet, and subsequently rebound when the ice sheet melts. Parts of northern England are still rebounding by up to 1 mm per year from being pressed down by the last, Devensian, ice sheet.

Purpose of the case example

The southern North Sea Basin is presented as a case example, because the land bridge to Europe played a critical role in faunal migration from Europe during the Quaternary, and because many of the coastal environments now observed in eastern England developed in response to the rising late Quaternary sea level. Reconstructions of the coastlines around the southern North Sea at 10,000 and 9,000 years ago are shown in Figure 23.

Description of the case study area

Evidence of past change

Surveys of the bathymetry and sea bed sediments in the southern North Sea have revealed a wide variety of relict bedforms, many of them of glacial origin, that do not relate to the present day sea level and wave current regime. Perhaps most conspicuous are the dendritic channel networks that, although in part excavated by scouring of glacial meltwaters, also indicate drainage from the land area during lower sea levels. Intertidal sediments found at great distances offshore, and probable beach gravels, indicate former shorelines in the offshore area. By using computer images of the sea floor, it is possible to recreate the shape of the land areas around the southern North Sea at lower Holocene sea levels.

Further evidence from the geological record

Rock sequences from the Carboniferous Period (360 to 280 million years ago) provide some of the best evidence in English rock record of fluctuating sea levels.

Warm, tropical seas once covered England on more than one occasion in the geological record when the continental crust of Europe was located closer to the Equator. For example, the shell-rich limestones of the Great Scar Limestone Group of the Malham area reveal that for a long period of time, from 360 to 325 Million years ago, shallow tropical seas covered uplifted blocks on the Yorkshire landscape such as the Askrigg Block. An apron reef and associated knoll reefs (Craven Reef Belt) developed along the southern margin of the Askrigg Block. For a substantial part of the the Cretaceous period, between 94 and 70 million years ago, warm tropical seas covered much of southern and eastern England. The white Chalk, a familiar component of the English landscape, is composed almost entirely of the microscopic calcite plates of algal phytoplankton known as coccoliths, which flourished in the warm Cretaceous seas (Figure 23). It is unlikely that warm tropical seas will ever cover England again, because the formation of new sea floor along mid-ocean ridges has caused the gradual movement of continental crust on plates around the globe over geologic time, moving the British Isles away from the Tropics.

The study of ancient limestone rock sequences formed in these tropical seas still provides interesting lessons, particularly on the frequency of sea-level changes. Cyclicity is recorded in Carboniferous Dinantian limestones on the Askrigg Block, which were also subject to worldwide or eustatic sea-level oscillations, related to the repeated growth and decline of the Carboniferous ice sheets that existed at the time in the Southern Hemisphere. These eustatic sea-level changes resulted in periodic emergence of the platform carbonates. The evidence for this within the limestone sequence is provided by somewhat undulating palaeokarst solution surfaces, immediately underlain by relict plant rootlet structures and sometimes by crusts developed by soil-forming processes. In addition, the platform limestones show a number of thin shale beds or “clay wayboards” which are altered volcanic ash layers, some of which coincide with the palaeokarst surfaces (Fig. 24)

The most characteristic feature of the Carboniferous Coal Measures succession is its small-scale cyclic nature where each of numerous cycles represents a gradual change from marine mudstone deposition to non-marine mudstones and sandstones, deposited in rivers channels and overbank floodplains, with the whole basin finally stagnating with the establishment of the vegetated swamps that ultimately formed the coal seams. This transition is represented in the rocks by marine mudstones, non-marine mudstones, sandstone and seatearths, and coal seam itself. The picture that finally emerges is of deposition in a river-dominated, waterlogged coastal plain with luxuriant, freshwater marshes separated by meandering, sand-filled rivers that occasionally burst their banks to flood across the adjacent lakes or plains. Periodically a rise in global sea-level saw the whole of this low-lying coastal plain area temporarily flooded by the sea. These basin-wide flooding events produced thin mudstone-dominated intervals that have rich marine faunas that include brachiopods, bivalves and most notably the ammonoids (*Goniatites*) *(Illustration needed).* They are known as Marine Bands, and about 24 such events are recognised in the succession with the most extensive of them forming key surfaces in the stratigraphic subdivision of the Coal Measures Group. Correlation of these marine bands has extended into the coal-bearing sequences of Europe and the USA. Estimates vary, but these flooding events appear to have recurred every 100,000 years. In the rock succession, however, there is evidence of other minor marine flooding events suggesting that the periodicity of these global sea-level rises may have been even closer.

Two main types of cycles can be recognised from studying the general rock succession. The first follows a simple pattern of localised subsidence of the largely freshwater vegetated swamps, allowing migration of river channels, inundation by silt or sand-laden floodwaters. Eventually a gradual recovery occurs as floodwaters subside and the vegetation re-establishes itself to begin a new period of growth. Correlation of these essentially localised flooding events is only possible over limited areas. The second type of cycle is much more significant and develops as a result of external forces which cause a periodic rise in global sea-level and consequent regional flooding of the basin by the sea. Such sea level rises, in the Late Carboniferous, have been related to fluctuations in the extent of polar ice sheets, a situation mirrored by present day sea-level rises.

These Carboniferous examples show, just like in the Quaternary, that sea level fluctuations are normal events when ice sheets exist at high latitudes.

Implications and management options for the future

The cyclic nature of the Coal Measures succession in particular demonstrates how finely balanced the Earth's ecosystems have always been. Significant changes can clearly occur naturally both as a result of local subsidence or uplift effects, or as a consequence of global climatic events initiated far away from the areas they effect. The relatively rapid transition from a luxuriant coastal plain to a shallow marine shelf sea covering a large part of the northern hemisphere were generated by repeated global sea level rises due to the spasmodic melting of the polar ice sheets. Today the present polar ice caps are also showing unequivocal evidence of ice melt and a gradual rise in present-day sea levels is likely to be the consequence. Whether the consequences will be as dramatic as those in the Late Carboniferous we must wait and see.

The present trend of rising sea level cannot be prevented. Decision makers now need to plan for an estimated 80 cm average rise in sea level around the coast of England by 2080, according to the latest IPCC predictions. Effectively this means that all new development should be directed away from the vulnerable sections of coastline. Planners also need to make some strategic decisions on whether to allow wetland regeneration on parts of the very low-lying coastal agricultural areas, such as in the Fens and the Somerset Levels. Agricultural land drainage costs may no longer become economically viable against a trend of rising sea level. Restoration of natural wetland habitats could be a major benefit of sea-level rise.

3.2 VOLCANIC AND TECTONIC EVENTS

3.2.1 Volcanic eruptions

Introduction

Explosive volcanic eruptions send up clouds of ash into the atmosphere. This ash, which may be carried by winds over long distances, subsequently settles across the surrounding areas. Volcanic ash falls on land are usually washed downslope by rainfall and are rarely preserved *in situ*, but ash fall deposits have a relatively high chance of preservation in low energy marine and lake environments where the ash is gradually covered by the normal background sedimentation. During sediment burial, much of the volcanic ash changes chemically and physically into clay minerals but nonetheless the ash beds usually retain some characteristic grains and textures diagnostic of a volcanic origin which are still visible when viewed under a microscope. In field exposures the ash bands frequently weather to a conspicuously different colour and texture from the enclosing sediments. Ash bands are laterally continuous and geologists use them to correlate rocks or sediments across wide areas.

Purpose of case study

The presence of ash bands within English rock sequences is a reminder that this part of the world has often, and could be affected at any time in the future, by ash falls from volcanic eruptions. Ash bands in the London Clay, now exposed in the Stour estuary, provide a record of the frequency of volcanic ash falls over London 50 million years ago.

Description of site

The London Clay exposed at Wrabness is a sequence of typically dark bluish grey to brownish grey mudstones including 32 beds of altered volcanic ash (Figure 25). The exposure forms part of a sequence that can be traced from the south Essex and north Kent coasts where it reaches up to 150 m in thickness, thinning westward under London to Wiltshire where only remnants remain, less than 5 m in thickness.

The London Clay Formation was deposited in a shallow marine basin, fringed by coastal swamps and tropical rainforest during the Eocene period. The evidence for this is provided by the numerous seeds and fruits of mangroves, palms, magnolia, dogwoods, laurel, cinnamon and bay that are fossilised in the mudstones. But ash bands visible in borehole cores from the London Basin and at coastal exposures reveal that the coastal swamps were frequently blanketed by volcanic ash from distant volcanoes.

Evidence of past change

The basal part of the London Clay includes more than 40 distinct volcanic ash beds, and abundant disseminated ash debris indicating that additional, thinner, ash layers may have been destroyed by contemporaneous reworking of the sea floor sediments by burrowing organisms. These ash bands are part of a record of Tertiary and Quaternary volcanic activity that dates back over 50 million years to the start of the opening of the north Atlantic ocean, and continues to the present day in Iceland.

The ash bands in the basal sections of the London Clay relate to the latest Palaeocene and early Eocene phase of explosive volcanism in the Faeroe-Greenland area which deposited ash falls across the whole North Sea Basin and adjacent areas. These ash bands are the sedimentary record of the separation of Greenland from Europe. More than 200 separate ashfalls have been recognised in the North Sea area.

Impacts of past and present change

It is difficult to ascertain from the rock record the magnitude of the impact of these ashfalls on the London Clay environment. Undoubtedly vegetation on the surrounding land-masses will have been destroyed when the blanket of ash was extensive, but it is unlikely that the falls were of such magnitude to cause extinction of species.

Further evidence from the geological record

The rugged scenery on the central fells of the Lake District is largely due to extensive exposures of extrusive volcanic rocks known as the Borrowdale Volcanic Group. Today the compacted lavas, tuffs and agglomerates still exceed 4000 m in thickness and serve as a reminder that Cumbria was once a major centre of volcanic activity in Ordovician times, between 500 and 435 million years ago. Some of the well-bedded tuffs that are used as Westmorland or Cumberland green slates may have been deposited in water. However, the vast majority of the tuffs and lavas are believed to have been deposited on land on account of the lack of diagnostic marine fossils or sedimentary structures.

Volcanic activity can also cause doming of the land surface or seafloor, which can cause local tectonic effects and induce local fluctuations in relative sea level. A major volcanic dome occurred beneath part of the present North Sea area within the Middle Jurassic period, between 174 and 149 million years ago, and was part of the reason for the existence of a northern landmass at this time. Evidence for which is provided by frequent occurrences of volcanic rocks of Middle Jurassic age in rock cores drilled in the North Sea in search of hydrocarbons. The dome began to subside as the lava was extruded. The effects of such subsidence, which was probably intermittent at first rather than a single catastrophic event, allowed the sea to briefly transgress into the North Yorkshire area, before further doming caused another retreat. The marine environments that dominate the Middle Jurassic succession further south in England did not succeed in establishing themselves in the North Yorkshire basin until very late in the Middle Jurassic. At this time the largely collapsed volcanic dome allowed rising global sea levels to flood this rifted northern landmass; marine sedimentation subsequently dominated the area.

Implications and management options for the future

The presence of volcanic ash in Quaternary and Holocene sediments in Europe is a reminder that the climate of the British Isles could still be affected by volcanic eruptions in other parts of the world at any time. While large eruptions in Iceland would be most likely to affect England, the effects could be felt from volcanic eruptions much further afield. It should be remembered that the Mount St. Helens eruption generated a huge ash cloud that rose 20,000 metres into the atmosphere, and subsequently ash was distributed across a wide area. The eruption of Tambora in Indonesia in 1815 was so catastrophic that the amount of ash sent up into the atmosphere caused global temperatures to fall by 0.5 ^{o}C and unusually heavy rain severely curtailed the 1816 growing season in England. However, the effect on global temperatures lasted for little more than two years. The largest Holocene eruption in Iceland related to the Thjorsa lava eruption, dated to approximately 8600 years ago, which affected the weather of the whole northern hemisphere. It's not a matter of if, but when there will be another volcanic eruption that will affect the climate of England! However, we can be sanguine in the thought that volcanic impacts on climate are mostly short-lived.

3.2.2 Earthquakes

Introduction

Minor earthquakes are commonly recorded in England, but major events causing structural damage to property are rare. This is because England lies a considerable distance from the boundary edges of the Eurasian Plate and therefore is less likely to be affected by major earthquakes that are generated by the friction between moving plates.

Purpose of case example

Earthquakes generated along deep-seated reactivated faults can nevertheless occur occasionally in England. The earthquake in Colchester on 22nd April 1884 is chosen because it occurred in a tectonically inactive area, and because it was a sizeable event with a possible magnitude of 5.0-5.5. Its occurrence could not have been predicted.

Description of study site

All evidence of damage from the 1884 earthquake has been removed, so evidence is based wholly on historical documents and still visible contemporary repair work undertaken on damaged buildings. Historic reports indicate damage to more than 1200 buildings, including 31 churches in the Colchester area. Three deaths that resulted from fallen masonry were reported at the time in the Illustrated London News.

Evidence of past change

Apart from historical records, it is highly unlikely that evidence for small earthquakes would be preserved in the Quaternary sediment record in East Anglia. However, although generally regarded as a stable part of England, parts of the region have experienced some gentle tectonic flexuring and extension related to downwarping in the southern North Sea Basin during the early Quaternary, and thus may not be completely stable as has generally been thought. Earthquake risk was a factor considered prior to construction of the Sizewell B nuclear reactor on the Suffolk coast.

Impacts of past and present change

The type of structural damage to property caused by earthquakes in England is similar to that resulting from severe storms, such as toppled chimney stacks and fallen trees. Earthquakes will not lead to environmental change in England.

Further evidence from the geological record

Evidence for earthquakes in the geological record is invariably indirect, apart from evidence in the recent archaeological record. The occurrence of large-scale disruption of sedimentary units in the rock record is often attributed to ancient earthquake events. Earthquakes are frequently proposed as mechanisms for triggering landslides, and highly contorted beds are sometimes explained as having been caused by earthquake-induced liquefaction of highly saturated sediments.

Implications and management options for the future

It is impossible to predict the occurrence of earthquakes caused by re-activation of faults. The very existence of these deep-seated features is often debatable due to incomplete seismic mapping of deep onshore structures. Monitoring of all seismic events in England is undertaken by the British Geological Survey. Their past records indicate that the occurrence of earthquakes capable of causing minor structural damage to buildings such as toppled chimney stacks are infrequent events, typically one every ten years. Such a ten-year event occurred on 23rd September 2002 when an earthquake measuring 4.8 on the Richter scale, with an epicentre in Dudley in the West Midland, caused shaking of buildings across wide areas of central England and Wales. Buildings are usually well constructed in England and specific planning measures are generally not needed for earthquake hazards.

3.3.3 Folding and faulting

Introduction

Relative to many other parts of the world, England is not an area where sediments and rocks are being actively folded or fractured at the present day. But we do not have to go far back in the geologic record to find evidence that the rocks beneath our feet have been subject to tectonic stresses and strains on many occasions. Glacial tectonic structures relating to Quaternary ice sheets most recently affected England, but older tectonic processes were on a much larger scale and tended to relate to the movement of continental blocks across the Earth's crust.

Purpose of case study

Spectacular examples of chevron or concertina folding are exposed in cliffs on the north Cornish coast in the vicinity of Crackington, approximately mid-way between Boscastle and Bude (Figure 26). This example is an extreme illustration of the severe tectonic stresses that have, at times, affected the English landmass.

Description of case study area

The cliffs in the vicinity of Crackington are composed of highly folded late Carboniferous (Namurian) sandstones and shales, with spectacular examples of zig-zag fold structures. Individual folds have straight limbs and sharp hinges corresponding with lines of fracture.

Evidence of past change

The folding is believed to have been caused by compression and crumpling of the strata towards the centre of an east-west trending fold belt during the late stages of the Variscan mountain building era, which affected Europe from the late Carboniferous to the Permian. The relatively thin Carboniferous sandstone beds were particularly susceptible to crumpling under stress, with fracturing occurring at the more acute folded limbs.

Impacts of past and present change

Further evidence from the geological record

Rocks have commonly been deformed by plate collisions, but unconsolidated sediments and weak rocks may also be deformed by moving ice. Glacial folding and faulting would be a serious issue for England if we again moved into a full glacial period, as important an effect as falling temperatures. A prograding ice sheet has the power to destroy any man-made construction in its path. To illustrate the sheer power of an ice sheet, the tectonic structures exposed in cliffs of glacial sediments in north Norfolk are impressive. Most dramatic of all are large chalk blocks, the largest reaching 30 m in length, which have been thrust up from the contiguous bedrock by the force of the overriding glaciers (Figure 21). These chalk blocks are largely undeformed, preserving their original bedding surfaces with aligned flints, suggesting probable transportation in a frozen state. These displaced chalk blocks demonstrate the sheer power of a moving ice sheet.

Implications and management options for the future

Folding and faulting occurs over long periods of geologic time and England is unlikely to experience any tectonic effects in the foreseeable future.

3.3.4 Tsunamis

Introduction

Large tidal waves or tsunamis are recognised as a potential threat around the margins of the Pacific where great loss of life in Japan, Hawaii and Papua New Guinea has occurred within the past century. It is generally not appreciated that the coastline of England could also be at risk from large tidal waves.

Purpose of case study

To show that there is a small but nevertheless real risk that coastal areas of England could be affected in the future by tsunamis caused by distant submarine landslides. Such short-lived but catastrophic events could instantaneously destroy delicate coastal habitats.

Description of case study area

The possible risk to low-lying parts of the coastline of southwest England from a tsunami generated by collapse of the side of a volcano in the Canaries archipelago was recently given extensive publicity by reports from the Benfield Greig Hazard Research Centre, University of London. Although publicity for the tsunami risk may have been timely, it is highly contentious that collapse of part of La Palma could generate a large tidal wave on the scale envisaged by the

University of London researchers. However, few people realise that southwest England has been affected by a tsunami as recently as 1755.

Within about 6 hours of the major earthquake which occurred at Lisbon in Portugal on 1st November 1755, a tsunami hit southwest England, washing offshore sands, gravels and boulders inland. Some of these sediments have been preserved in inland lakes, such as that of Big Pool, St Agnes, on the Scilly Islands, where a 15 to 45cm thick layer of coastal sands is enclosed within peats and muddy deposits. Dating of the peats has provided confirmation that the sands were deposited as a result of the 'Lisbon tsunami'. Similar, though older marine sediments, occur in other inland settings, suggesting that other tsunamis may have influenced the coast during the Holocene. Maybe the submergence of the lost land of Lyonesse, between mainland Cornwall and the Isles of Scilly according to Cornish legend, resulted from a tsunami!

Tsunamis not only threaten southwestern England. Geological evidence shows that a large submarine slide area known as the Storrega Slide off the northwest coast of Norway caused a major tsunami in the northern North Sea a little over 7,000 years ago. The tidal wave affected the coast of northeastern England as well as large parts of Scotland. Today large parts of the North Sea coastline remain vulnerable to tsunamis generated by submarine landslides on the Norwegian shelf. The slope sediments in the Storrega area contain accumulations of gas, and remain particularly prone to instability.

Further evidence from the geological record

Tsunami deposits are rarely reported from ancient coastal succession. Their deposits could be preserved as marine flooding horizons in the geological record, but it would be very difficult to distinguish a marine incursion event caused by rising sea level from a short-lived tsunami flooding event. Tsunami deposits can only be positively identified when the age of the sediments correlates exactly with the date of a causation event, be it a major landslide or an earthquake.

Implications and management options for the future

The tsunami hazard is a concern to all low-lying areas around the coast of England, particularly those with large residential populations or with key infrastructure such as ports or nuclear power stations. Tsunamis occur infrequently and cannot be planned for, at least not in England. However, the large loss of life in Lincolnshire and Norfolk following the storm surge floods of 1953 should serve as a warning of the potential catastrophe that a tsunami could unleash on the English shoreline. It would appear that coastal areas most at risk from tsunamis are likely to be those areas that are also most at risk of marine flooding during storms or spring tides. In general, developments in flood-risk coastal areas should be discouraged where defences against marine flooding and the predicted rise in sea level are inadequate. Moves by the insurance industry, whereby housing in high-risk areas is very expensive or impossible to insure, may influence policy on land use in low-lying coastal areas.

4. Changing life

4.1 EVOLUTION AND EXTINCTION OF SPECIES

Introduction

It is now recognised that climate change is inevitable due to changes in the Earth's orbit around the Sun in a cycle lasting about 100,000 years, together with more frequent natural oscillations in the tilt of the Earth's axis. Nevertheless, studies of ice cores have shown that temperatures and environments can remain broadly stable for tens of thousands of years, before sudden changes occur, often over just a few tens of years. It is these rapid climatic change events that threaten the existence of flora and fauna. Local floras and faunas are subjected to increasing stress as they attempt first to adjust, then to re-adjust, to extreme fluctuations in local environments. Some species thrive while others are decimated as local conditions change.

Purpose of case studies

Examples of both floral and faunal change have been chosen to illustrate the biological impacts of environmental change.

The Yorkshire “meres” are lakes with virtually uninterrupted sedimentation records for the past 12,000 years. As the post-glacial vegetation colonised the Humberside area, pollen trapped within the lakes records the evolution of vegetation types. The abundance of organic material can be readily dated by radiocarbon techniques, providing a guide to the rate of change of vegetation types in the area (Figure 27).

Quaternary mammals provide one of the best examples of species evolution and extinction due to climatic stress, because it is possible to date with reasonable accuracy the fossil remains of extinct species found at many sites in England, and thereby assess their rate of evolution. The increase in size of the horse is one example of an evolutionary trend documented in the sediment record. Human evolution is also marked, but fossils are very rare. Extinction of species such as the sabre tooth cats and Irish elk occurred because climate change led to a change in their habitat and gradual loss of their food supplies. The final demise of the sabre-toothed cats can be traced back to 35,000 years ago when climate change led to colder weather. This led to the extinction of the large herbivores, which were the main prey of the sabre-toothed cats. This in turn led to starvation of the sabre-toothed cats, which could be outrun by the smaller, surviving herbivores. Their demise was probably quickened by competition for food from other cat species such as the lion. The Irish elk also succumbed to loss of habitat, in this case the loss of grasslands accompanying a cold period lasting 1300 years known as the Younger Dryas which began 12,700 years ago, believed to have been caused by interruption of the Gulfstream in the North Atlantic.

Description of case study areas

As the ice sheets receded at the end of the last (Devensian) glaciation, lakes locally known as “meres” developed in hollows on the till outcrop in the vicinity of Grimsby on Humberside. These lakes survived until relatively recent times, but have been infilled in urban areas and are succumbing to modern agricultural methods in rural areas.

The deposits of the ancestral River Thames are chosen because faunal remains in the river deposits are relatively common, in part due to the numerous quarry exposures, and because the deposits span a sufficient interval of time over which the climate fluctuated markedly. The environment of the ancestral River Thames is described in section 2.2.2.

Evidence of past change

Borehole cores have been recovered from several lake deposits providing the most complete record of the vegetational and climatic variability in the area (Figure 27). Analysis of pollen from throughout the core documents numerous changes in vegetation in the last 12,000 years since the last glaciation. As the ice sheets retreated and temperatures increased, the open landscape around the lakes was initially colonised by herbs and small trees such as birch (Betula) and willow (Salix). A period of marked climate cooling between 11,000 and 10,200 years ago (loch Lomond stadial) with lower rainfall led to a loss of many trees judging by the dramatic reduction in arboreal pollen in the cores, and proliferation of sedges (Cyperacea), consistent with the development of tundra vegetation. With subsequent warming from 10,0000 years ago, the lakes shrank and developed into swamps with a predominance of shrub vegetation in their vicinity, with the presence of alder, elm, lime and oak pollen indicating the existence of deciduous woodland beyond the limits of the swamps. This evolution of vegetation continued into historic times with the re-emergence of open water lakes in the area.

The presence of ice wedge casts in the ancestral Thames sediments are an indicator of a cool periglacial climate, but the sediments deposited on terraces by the River Thames hold floral and faunal evidence of a warmer, interglacial, climate as well as well. For instance, at Aveley in Essex, the bones of two different species of elephant have been found in the same sequence. Beds containing the straight tusked elephants, *Palaeoloxodon antiquus,* which is thought to have lived in relatively warm interglacial environments are overlain by peat containing bones of the mammoth *Mammuthus primigenius*, a species that survived in much harsher, cooler temperatures. These deposits are thought to represent the penultimate interglacial that occurred around 200,000 years ago.

Similarly, at Swanscombe in Kent, assemblages of mammals and molluscs have been discovered that represent interglacial conditions. Fallow deer bones have been found indicating a temperate period, though pollen data show a complex succession of climatic fluctuations. Clacton-on-Sea is a site of similar age to Swanscombe, where freshwater beds yield the remains of a rich mammalian fauna including lions, straight-tusked elephant, rhinoceros, red deer and horse. Pollen in the sediments also indicates a temperate period with established deciduous woodland, which evolved over time to coniferous woodland as temperatures cooled.

Underneath Trafalgar Square silty deposits laid down by the ancestral Thames contain the remains of straight-tusked elephant, narrow nosed rhinoceros, cave lion and hippopotamus, indicating a warm interglacial environment at the time of deposition, approximately 120,000 years ago.

Impacts of past and present change

Since the Bronze Age the vegetation cover of England has been affected by the widespread felling of trees, but pollen records trapped within sediments provide the most important means of documenting the significant changes in vegetation that have occurred throughout the Quaternary. The pollen record indicates that major changes in vegetation can occur over a period of just a few tens of years. The evolution of the vegetation cover relates to the evolution and extinction of mammals, both being ultimately controlled by climate change.

The ancestral Thames deposits contain fossils that may be used to demonstrate the extinction of species from the area as a result of fluctuating climatic conditions. This includes loss of “African” species that lived in the Thames valley during the glacials, as well as cold weather species such as mammoths and bears during the interglacials.

Further evidence from the geological record

The science of biostratigraphy is based on the premise that species evolve over geological time and that rock units can therefore be characterised by their unique fossil assemblage. This applies to the flora (pollen and plant remains) as much as to the fauna. Marine gastropods, and in particular the ammonoidea, were used to establish the fundamental stratigraphic sequence within the Jurassic system. The morphology of fossil ammonite shells and the shape of suture lines on the outside of their shells changed frequently throughout the Jurassic system. The ammonite fossils were sufficiently numerous that an evolutionary sequence of morphological changes could be used to establish the relative age of rock sequences. The stratigraphic sequence deduced from fossil ammonites is still largely valid today, although microfossils such as foraminifera are now used to refine the sequence.

Implications and management options for the future

When climate change occurs rapidly, there is little time for natural migration to occur, especially in the case of vegetation. Some species that can't adapt are naturally driven into extinction, whereas others are able to evolve to survive in the changed conditions. There now needs to be a clear distinction between species that are being driven to extinction by human-induced habitat loss, which could be rectified by returning excess agricultural land to wildlife habitats, and species loss due to natural climatic changes.

4.2 MIGRATION OF SPECIES

Introduction

Migration is a standard response of many species to the changing seasons at the present day. Flocks of birds migrate south to over-winter in the Northern Hemisphere. Similarly, many larger mammals migrate to new pastures. Scientists believe this pattern of migratory behaviour also occurred in the past, though it is more difficult to prove. Large numbers of dinosaur footprints facing the same direction on a rock surface may be interpreted as rare evidence of migrating herds of plant eating dinosaurs.

In addition to these seasonal migration patterns, there are longer-term, and sometimes permanent migrations of species as a result of climate change. This is a key issue at the present day with regard to biological SSSIs, where climate change could drive species from what has been assumed to be their natural habitats. The appearance in southern England of some bird and insect species more normally associated with Mediterranean climates may be a natural response to global warming, with supposedly indigenous species migrating north into Scotland. Plants are not as mobile as birds, insects and mammals and shifts in their geographic distribution tend to occur over a longer time period, but nevertheless the geographic range of plants is also anticipated to change over the next few decades if climate change continues.

The migration of our ancestors into England over the European land bridge when sea levels were much lower during glaciations is an important example to remember, where climate change, the search for new hunting grounds, and possibly rising populations were driving forces.

Quaternary fossils record the appearance and disappearance of species from an area, but migration events can only be distinguished from extinction and evolution effects by building up a regional picture of such fossil occurrences. Evolution and migration may go hand-in-hand if a climate change event is long lasting.

Purpose of case study

Species migration can be easily recorded at the present day, but it is difficult to prove species migration as distinct from species extinction in the rock record. Information about a species distribution in the rock record from a wide area would be required. Though their fossils are comparatively rare, large Quaternary mammals can be used to demonstrate migration across continents in response to climate change. Recent discoveries of mammoth fossils in Quaternary sediments can be used as indicators of species migration due to environmental change. The most advanced Woolly Mammoth that evolved in Siberia was able to migrate south as temperatures cooled. At the end of the last ice age the Woolly Mammoth migrated back northwards again to Siberia, where it evolved into smaller forms before finally succumbing to the warming climate.

Description of site

In 1990 the biggest, oldest and most complete elephant fossil ever found in Britain was discovered in the cliffs at West Runton, North Norfolk. A full excavation took place in 1995. The fossil, estimated to be between 600,000 and 700,000 years old, turned out to be of a mature adult male of the species *Mammuthus trogontherii.*

Evidence of past change

Other remains of different mammoth species are being found in Britain and the rest of Europe and these are helping scientists understand their migration and evolution. Until recently, scientists believed that three species of European mammoth existed, one evolving gradually to the next. The earlier primitive species, *Mammuthus meridionalis* lived in the Early Quaternary to about 700,000 years ago. Following this, the more advanced elephant species called *Mammuthus trogontherii*, (the Steppe Mammoth) that existed between about 700,000 and 500,000 years ago. Finally *Mammuthus primigenius*, the Woolly Mammoth, evolved to survive harsh glacial environments, and lived between 350,000 years ago and the start of the Holocene, about 10,000 years ago. This has been questioned recently, due to the discovery of the latter two species of elephant together at the same site at Marsworth in Buckinghamshire, suggesting they lived side by side.

This could only occur by one species migrating into the habitat of the other species. What scientists now believe is the *M. trogontherii* evolved relatively rapidly to *M. primigenius* in Siberia, which was cooling much more rapidly than Europe, to adapt to the very harsh cold environment. Temperatures then cooled further across Europe, and *M. primigenius* also migrated south and encountered the less evolved *M. troigonterii* still living in Europe. The more primitive and less adapted *M.trogonterii* gradually died out as the *M. primigenius* thrived in the glacial, open treeless environment that had developed in Europe.

Impacts of past and present change

This is an example of how mammal remains found in the sediments laid down thousands of years ago, have helped scientists reconstruct climate change and understand how animals adapted and migrated. This can be used to improve the present understanding of our changing climate and the adjustments of flora and fauna that could follow. The lessons to be learnt from this research are that species migration and loss of species will inevitably occur with climate change.

Further evidence from the geological record

Caves provide valuable shelter to animals, and fossil bones and dung found in caves can reveal critical information on successive phases of human and animal occupation at a particular site during the Quaternary. Victoria Cave in limestones of the northern Pennines near Settle has revealed an assemblage of Ipswichian interglacial mammalian bones including straight-tusked elephant, rhinoceros, hippopotamus and hyaena from deposits in the lower parts of the cave, but higher in the cave the bones of arctic fox and grizzly bear were found. Neolithic and Romano-British pottery and human remains have been recovered from other caves in the area.

the scenery would therefore have varied depending on the glacial stage. During a glacial maxima the appearance of North Norfolk would not be dissimilar to ice margin areas seen in Iceland at the present day, with ponded lakes, glacigenic moraines and little vegetation. As the glaciers receded, a tundra landscape with frozen ground prevailed initially, to be replaced in turn by pine forests and deciduous woodland as temperatures increased towards the interglacial maxima.

Implications and management options for the future

The issue of species migration will become relevant to all biological SSSIs if the current trend in global warming continues. Climatic fluctuations will naturally alter the fauna and flora of an area, with species migrations into and out of an area and sometimes species extinctions. It is therefore difficult to preserve species at one particular site when the climate is changing without interfering with natural processes. Temperature is a key variable controlling species survival and temperature trends should be considered when decisions concerning species habitats are being made.

The discovery of faunal remains at West Runton and many other Quaternary sites depends on the natural erosion or anthropogenic excavation of the sites. Careful management of the sites is required.

5. Bibliography

Active geomorphological processes of environmental change

The changing coast

Aitkenhead, N., Barclay, W.J., Brandon, A., Chadwick, R.A., Chisholm, J.I., Cooper, A.H. & Johnson, E.W. 2002. British regional geology: the Pennines and adjacent areas (Fourth edition). British Geological Survey, Nottingham. 206pp.

Castleden, R. 1996. *Classic Landforms of the Sussex Coast*. The Geographical Association. 56pp.

Clayton, K.M. 1989. Sediment input from the Norfolk cliffs, eastern England – a century of coast protection and its effects. Journal of Coastal Research, 5, 433-442.

Cunliffe, B. W. 1980 The Evolution of Romney Marsh: a preliminary statement. Pp37-55 in : Thompson, F. H. *Archaeology and Coastal Change*. The Society of Antiquaries of London.

Eddison, J. 2000. *Romney Marsh. Survival on a frontier*. Tempus Publishing Ltd, Stroud.

Mason, S.J. and Hansom, J.B. 1988. Cliff erosion and its contribution to a sediment budget for part of the Holderness coast, England. Shore and Beach, 56, 30-38.

Valentin, H. 1971. Land loss at Holderness. In: Steers, J.A. (editor). Applied Coastal Geomorphology. Macmillan, London, 116-137.

Changing rivers

Green, C.P. and McGregor, D.F.M. 1999. Pre-Anglian gravel deposits of the River Thames and its tributaries between Goring and Cromer. Proceedings of the Geologists' Association, 110, 117-132

Hey, R. W. 1967. The Westleton Beds Reconsidered. *Proceedings of the Geologists' Association*. **78**:427-445

Rose, J., Whiteman, C.A., Allen, P. & Kemp, R.A. 1999. The Kesgrave Sands and Gravels: "pre-glacial" Quaternary deposits of the River Thames in East Anglia and the Thames valley. Proceedings of the Geologists' Association, 110, 93-116.

Unstable land

Brunsden, D. and Chandler, J.H., 1996. Development of an Episodic Landform Change Model Based Upon the Black Ven Mudslide 1946-1995. In: Anderson, M.G. and Brooks, S.M. (Eds), *Advances in Hillslope Processes*. J. Wiley, Chichester, 869-896.

Chandler, J.H. and Brunsden, D., "Steady State Behaviour of the Black Ven Mudslide: The Application of Archical Analytical Photogrammetry to Studies of Landform Change" , *Earth Surface Processes and Landforms* , 20 , 1995, pp 255-275.

Chandler, J.H. and Brunsden, D., "Photogrammetry, Historical Photography and the Evolution of the Block Ven Mudslide, 1946-1988: *Evidence of Dynamic Equilibrium. British Geomorphological Research Group Annual Conference* , Cambridge, 1995, 21 pp

Matthews, M.C., Clayton, C.R.I. & Rigby-Jones, J. 2000. Locating dissolution features in the Chalk. Quarterly Journal of Engineering Geology and Hydrogeology, 33, 125-140.

Waltham, A.C. and Dixon, N. 2000. Movement of the Mam Tor landslide, Derbyshire, UK. Quarterly Journal of Engineering Geology and Hydrogeology, 33, 105-123.

Waltham, A.C., Simms, M.J., Farrant, A.R. & Goldie, H.S. 1997. Karst and caves of Great Britain. Geological Conservation Review Series, Joint Nature Conservation Committee, Peterborough, 358pp.

Catastrophic environmental changes

The influence of glaciations

Arthurton, R.S., Johnson, E.W., & Mundy, D.J.C. 1988. Geology of the country around Settle. Memoir British Geological Survey, Sheet 60 (England & Wales). 147pp.

Bridges, E.M. 1998. Classic landforms of the North Norfolk coast. Geographical Association Classic Landform Guide, 52pp.

Bridgland, D.R. 1994. Quaternary of the Thames. Geological Conservation Review Series, Joint Nature Conservation Committee, Peterborough, 441pp.

Eyles, N., Eyles, C.H. and McCabe, A.M. 1989. Sedimentation in an ice-contact subaqueous setting: the Mid-Pleistocene "North Sea Drifts" of Norfolk, U.K. Quaternary Science Reviews, 8, 57-74.

Lambeck, K. 1991. Glacial rebound and sea-level change in the British Isles. Terra Nova, 4, 379-389.

Lunkka, J.P. 1994. Sedimentation and lithostratigraphy of the North Sea Drift and Lowestoft Till Formations in the coastal cliffs of northeast Norfolk, England. Journal of Quaternary Science, 9, 209-233.

Pounder, E., in preparation. Classic landforms of the Northern Dales. Geographical Association Classic Landform Guide.

West, R.G. 1977. Pleistocene geology and biology (second edition). Longman Group Ltd., 440 pp.

Volcanic and tectonic events

Banerjee, D., Murray, A.S., and Foster, D.L. 2000. Scilly Isles, UK: optical dating of a possible tsunami deposit from the 1755 Lisbon earthquake. *Quaternary Science Reviews (Quaternary Geochronology)*; 20: 715-718.

Dawson, A.G., Foster, I.D.L., Shi, S., Smith, D.E., and Long, D. 1991. The identification of tsunami deposits in coastal sediment sequences. Science of Tsunami Hazards, 9 (1), 73-82.

Freshney, E.C., Edmonds, E.A., Taylor, R.T. & Williams, B.J. 1979. Geology of the country around Bude and Bradworthy. Memoir fir 1:50,000 geological sheets 307 and 308. London, HMSO for the Geological Survey of Great Britain (NERC), 62pp.

Haflidason, H., Eiriksson, J. and Van Kreveld, S. 2000. The tephrochronology of Iceland and the North Atlantic region during the Middle and Late Quaternary: a review. Journal of Quaternary Science, 15, 3-22.

Long, D., Dawson, A.G. and Smith, D.E. 1989. Tsunami risk in northwestern Europe: a Holocene example. Terra Nova, 1, 532-537.

Knox, R.W.O'B. & Ellison, R.A. 1979. A Lower Eocene ash sequence in SE England. Journal of Geological Society of London, 136, 251-253.

Knox, R.W.O'B. & Morton, A.C. 1988. The record of early Tertiary N Atlantic volcanism in sediments of the North Sea Basin. In: Morton, A.C. & Parson, L.M. (eds.). Early Tertiary volcanism and the opening of the NE Atlantic. Geological Society Special Publication, 39, 407-419.

Scott, R.F. 1977. The Essex earthquake of 1884. Earthquake Engineering and Structural Dynamics, 5, 145-155.

Changing life

Evolution and extinction of species

Berridge, N.G. and Pattison, J. 1994. Geology of the country around Grimsby and Patrington. Memoir of the British Geological Survey, Sheets 90, 91, 81 and 82 (England and Wales). HMSO, London, 96pp.

Migration of species

Lister, A.M. and Sher, A.V. 2001. The origin and evolution of the woolly mammoth. Science, 294, 1094-1097.

Glossary of geological terms

Agglomerate	A pyroclastic rock containing fragments mainly greater than 2 cm in diameter.
Anglian glaciation	A glacial period that ended about 450,000 years ago that saw the maximum southward extent of ice sheets over England during the Quaternary.
Carboniferous	A stratigraphic system covering the span of time from approximately 360 to 280 million years ago.
Cyclothem	An informal term applied to a series of beds, deposited during a single sedimentary cycle, that are repeated in a succession through time. A term usually used in the context of Carboniferous deltaic sedimentation.
Devensian	The last glaciation to have affected England, lasting from 26,000 to 10,000 years ago.
Dinantian	A European stratigraphic stage name for part of the Lower Carboniferous which, in England, is characterised by limestones that were formed in shallow marine areas and basin mudstones which were deposited in deeper water.
Doline	A conical depression down which surface waters disappear in limestone areas, also known as a swallow hole.
Drumlin	An elongate oval hill or mound composed of compacted till and glacial gravels deposited under the ice and oriented parallel to the direction of ice movement. Drumlins usually have a blunt nose in the direction from which the ice moved.
Erratic	A fragment of rock, usually larger than pebble sized, which has been transported some distance from its source. The term is usually applied to glacially transported rock fragments.
Esker	Long, sinuous ridges of sand and gravel, often steep-sided and unrelated to the surrounding topography, deposited by sub-glacial or englacial streams.
Evaporite	A sedimentary rock such as halite (rock salt) or gypsum, resulting from the evaporation of saline water.
Gravel	A general term for sediment with grains greater than 2 mm.
Glacial outwash	Sheet-like deposits of sand and gravel washed out from the front of a glacier by meltwater streams and deposited beyond the end moraine of an active glacier. Also known by the Icelandic term “sandur”.
Holocene	The most recent period of geologic time since the end of the last glaciation, broadly equal to the last 10,000 years. Officially the Holocene period ended in 1950.
Ice-wedge cast	A sedimentary structure formed by the sediment filling of a space formerly occupied by a wedge of ice that has since melted.
Interglacial	A period of warmer climate and ice retreat between glaciations.
Isostacy	The condition of equilibium of the lithosphere (Earth’s crust and upper mantle) Loading, for instance by ice, leads to depression or isostatic downwarping; removal of load leads to uplift or isostatic upwarping.
Jurassic	A system lasting from c.200 to 135 million years ago, named after the Jura Mountains between France and Switzerland.
Kame	A type of moraine formed at the front of an essentially stagnant glacier. A kame terrace consists of stratified sand and gravel formed between a melting glacier and a valley wall.
Karst	A characteristic surface topography of limestone areas, named after the Karst region of the Dinaric Alps in southern Europ, in which the limestone is weathered in a characteristic manner.
Lag deposits	Coarse sedimentary deposits which remain *in-situ* following a sedimentary event. The early Holocene rise in sea level (transgression) caused erosion and reworking of the underlying Tertiary rock substrate and of Quaternary sediments lying on the sea floor. Reworking of sediments during the transgression and subsequently by tidal currents led to winnowing of the finer sediments, leaving extensive lag deposits ranging in texture from gravelly sand to cobbles. These lag deposits are normally less than 0.25 m thick.
Limestone	A sedimentary rock composed dominantly of calcium carbonate ($CaCO_3$).
Limestone pavement	A limestone bedding plane, often stripped of any sediment or soil cover by glacial scouring, that is composed of a grid of limestone blocks separated by solution fissures. Limestone pavements are a characteristic feature of karst scenery.
Moraine	A mound, ridge or other distinct accumulation of mostly unsorted, unstratified glacial till.
Mud	Sediment with grains finer than 1/16 mm in diameter (0.0625 mm).

Mudstone	A general term to describe an indurated sedimentary rock composed of mud and silt. In this sense the term mudrock includes shale. The term mudrock is also used in a more specific sense for a fine-grained sedimentary rock with a blocky or massive tecture.
Namurian	A stage of the Carboniferous system, between the Dinantian and the Westphalian. In England most Namurian rocks were deposited in river channels feeding deltas and as beds known as turbidites, deposited from waning energy density flows as slurries of sediment are carried over the delta front.
Pebble	A sediment component between 4 mm and 64 mm in diameter.
Periglacial	A term applied to a land area adjacent to an ice sheet, typically characterised by frozen ground, with frost-heave structures, wind-blown silt (loess), and scree and landslides resulting from frost shattering and repeated freezing and thawing of the surface layers of the ground.
Regolith	The loose material resting upon solid bedrock comprising varying amounts of soil and weathered rock fragments, glacial sediments, alluvium and wind-blown sediment.
Quaternary	A period of geological time from approximately 1.6 million years ago to the present which has been characterised by repeated glaciations (ice ages) separated by interglacial episodes of which the Holocene is the most recent.
Sand	Sediment with grains between 1/16 mm and 2 mm diameter
Sandstone	A sedimentary rock consisting dominantly of sand-sized grains.
Shale	A laminated, indurated rock composed dominantly of mud with a distinct tendency to split along closely spaced bedding planes.
Speleothem	A sedimentary deposit precipitated gradually from dripping or percolating water in a cave system, that can provide a record of climate change.
Till	A generally unsorted mixture of rock fragments and ground rock flour deposited by glaciers.
Triassic	A stratigraphic system covering the span of time from approximately 225 to 195 million years ago.
Tuff	Consolidated volcanic ash.
Westphalian	A stratigraphic stage name for part of the Upper Carboniferous which, in England, is characterised by coal-bearing deltaic rocks.

List of Figures

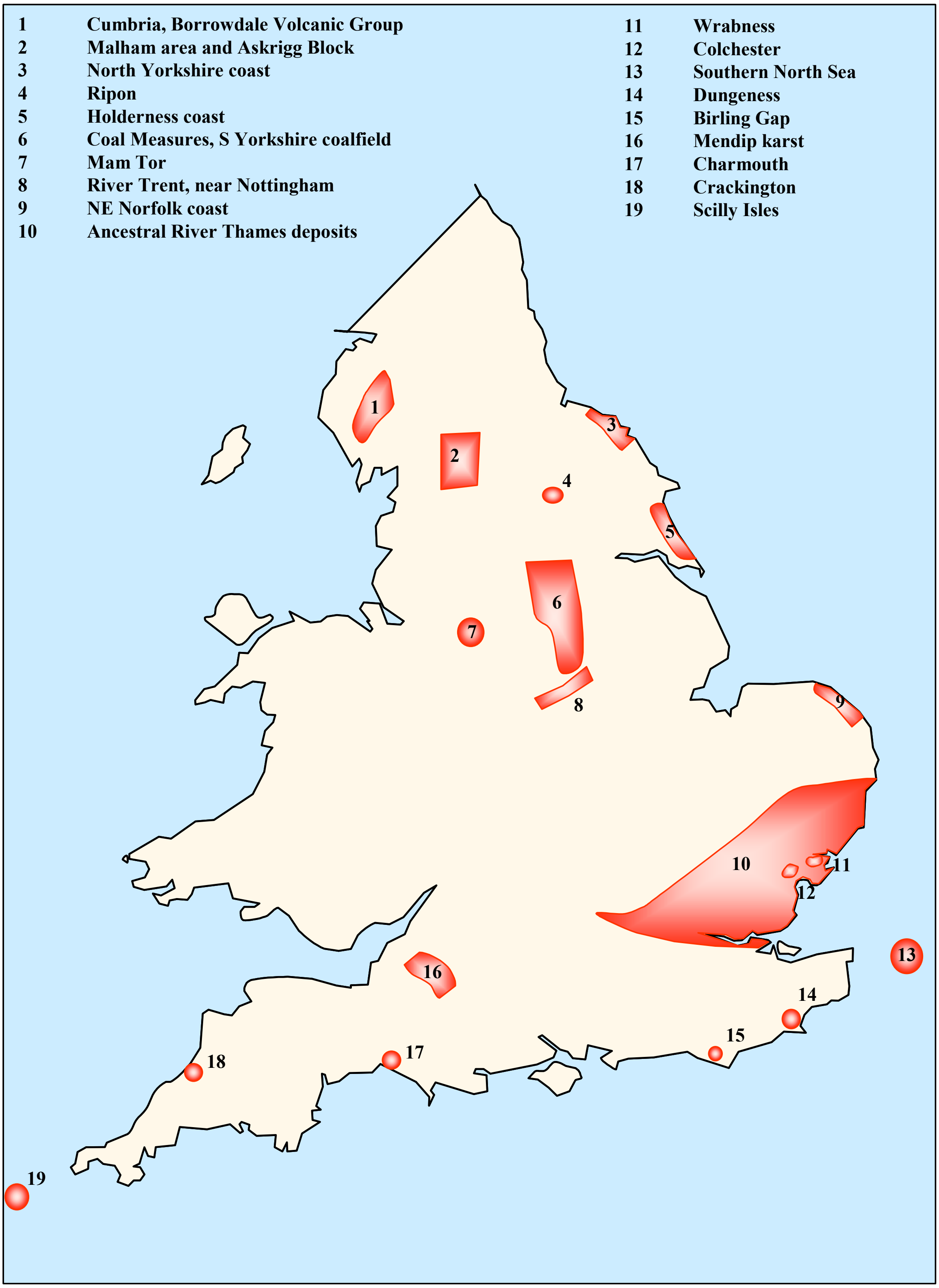


Figure 1 Locality of case examples and other key sites mentioned in the text

Figure 2 Erosion of the Holderness cliffs

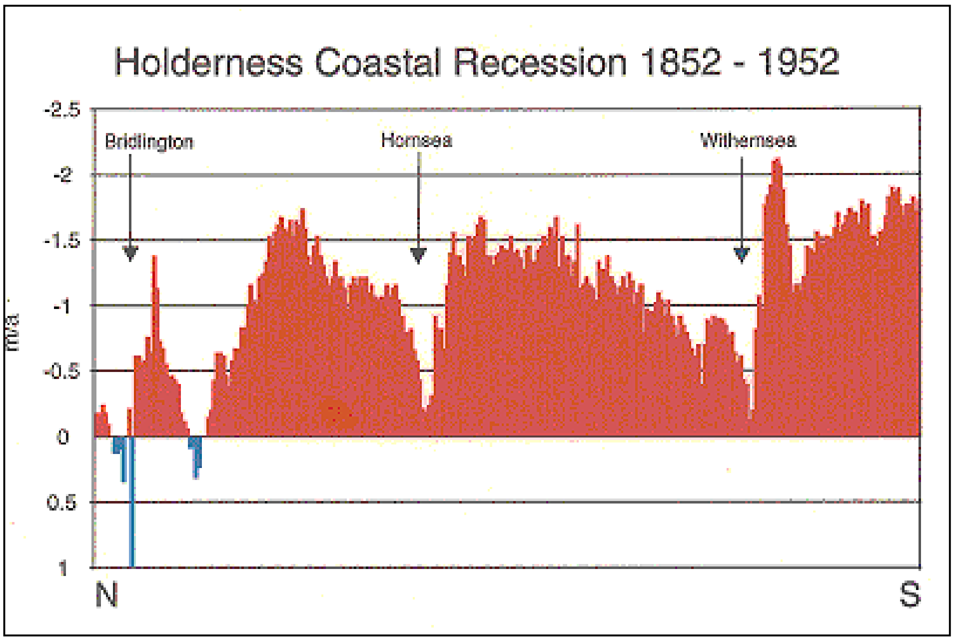


Figure 3 Rates of cliff retreat at Holderness

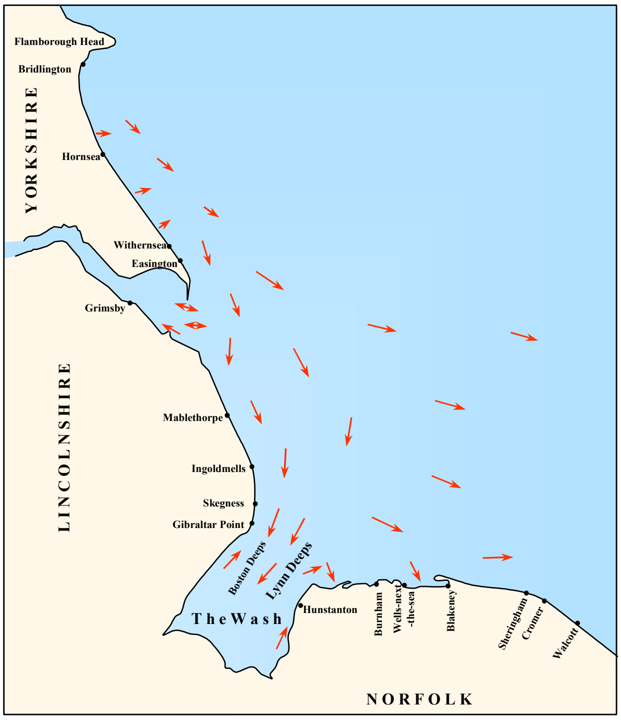


Figure 4 Fine sediment transport directions offshore from Yorkshire to Norfolk

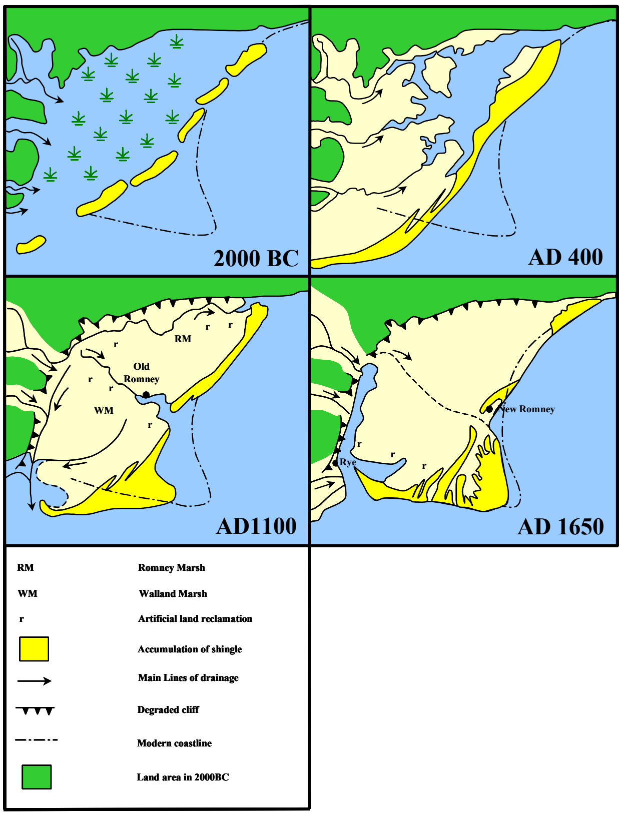


Figure 5 Simplified evolution of Dungeness Foreland, based on the work of Cunliffe (1980)

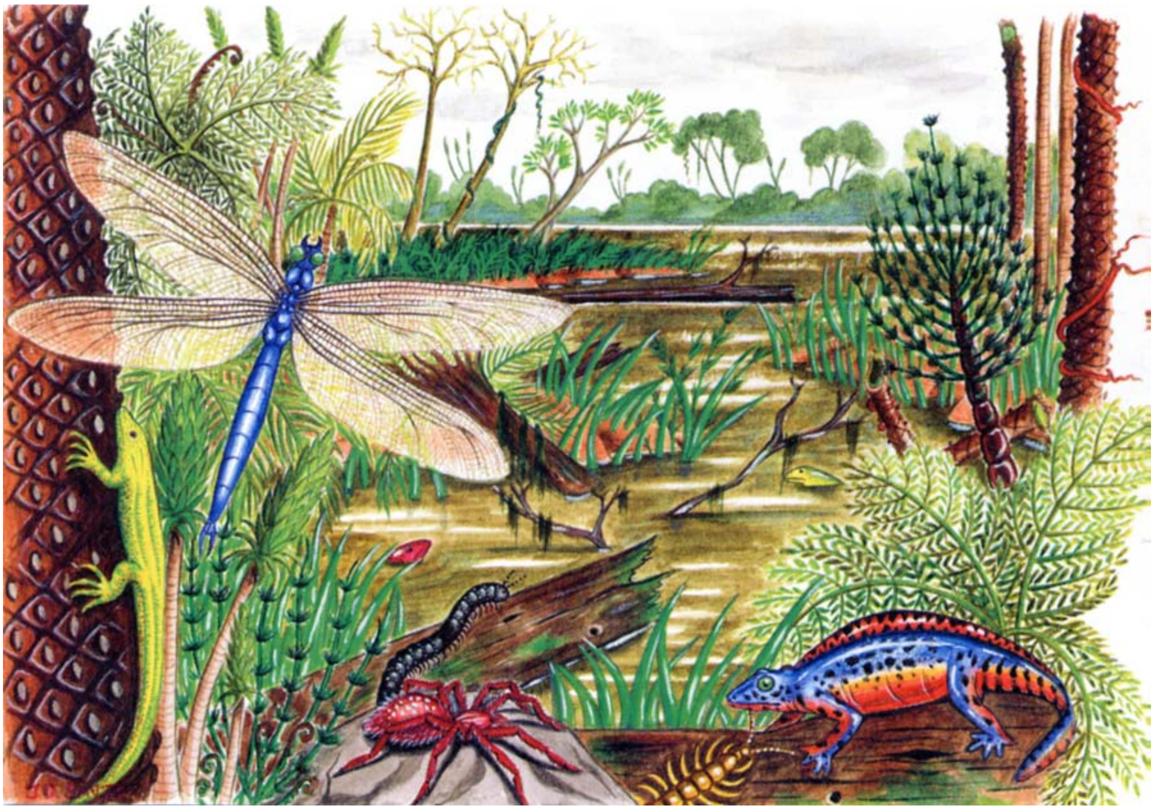
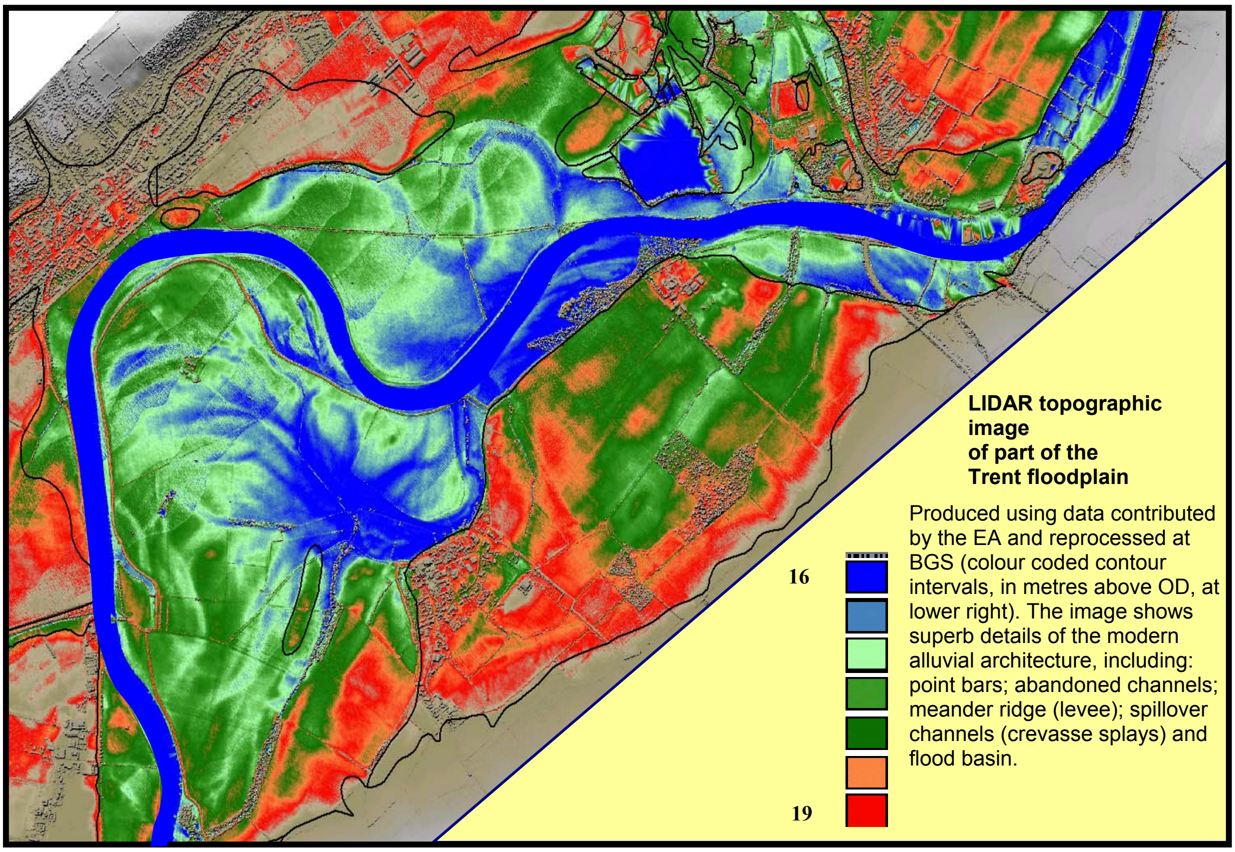


Figure 6 Carboniferous swamp environment

Coal swamps developed in many parts of England during the Carboniferous period, about 330 million years ago. Dense vegetation growing in humid tropical swamps consisted of large fern trees and lush undergrowth. As plants died their remains built up a thick layer of peat that was transformed in time into coal. Communities of insects including spiders, centipedes and scorpions inhabited the forest floor while dragonflies with a wingspan of up to 20 cm dominated the forest skies. Freshwater fish and amphibians lived in the shallow lakes and sluggish meandering rivers.© NERC.



LIDAR topographic image of part of the Trent floodplain

Produced using data contributed by the EA and reprocessed at BGS (colour coded contour intervals, in metres above OD, at lower right). The image shows superb details of the modern alluvial architecture, including: point bars; abandoned channels; meander ridge (levee); spillover channels (crevasse splays) and flood basin.

Figure 7 LIDAR image of the Trent valley showing the shifting position of the river channel

Figure 8 Flooding of the Trent floodplain, November 2000.
Photo, A. Forster © NERC

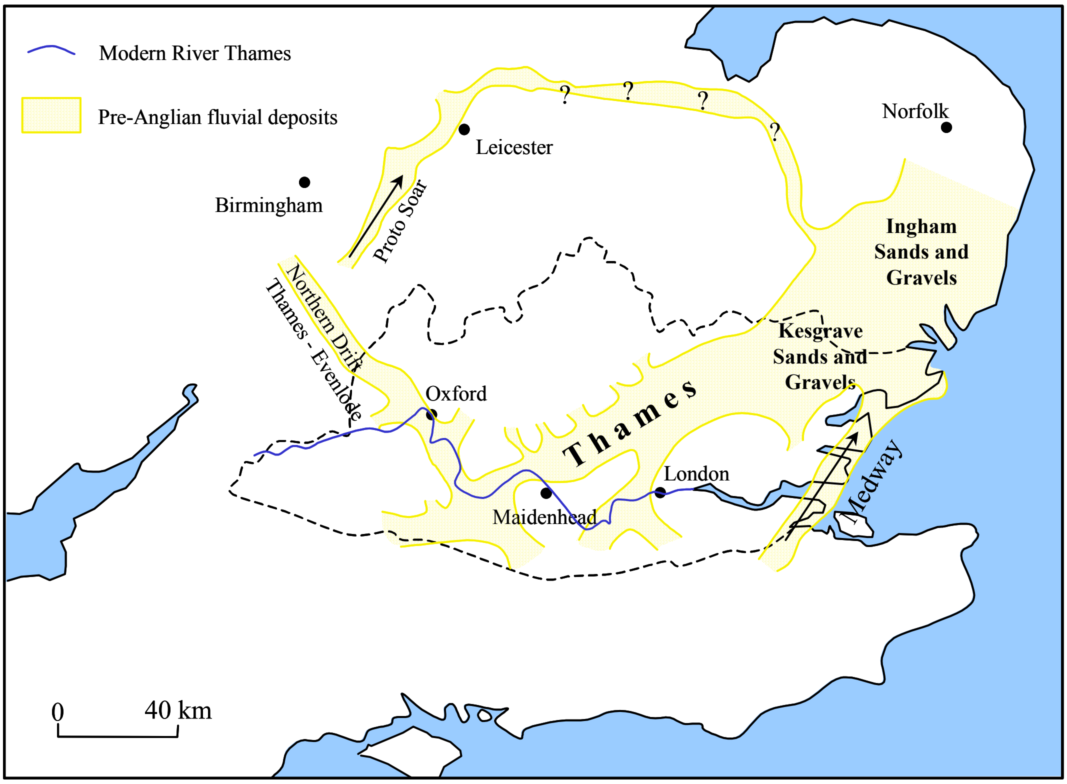


Figure 9 Course of the ancestral River Thames through East Anglia

Figure 10 Coarse grained deposits of the ancestral River Thames, Kesgrave Sands and Gravels © NERC

Figure 11 Lateral migration of channels in Jurassic rocks from the Yorkshire coast ©NERC

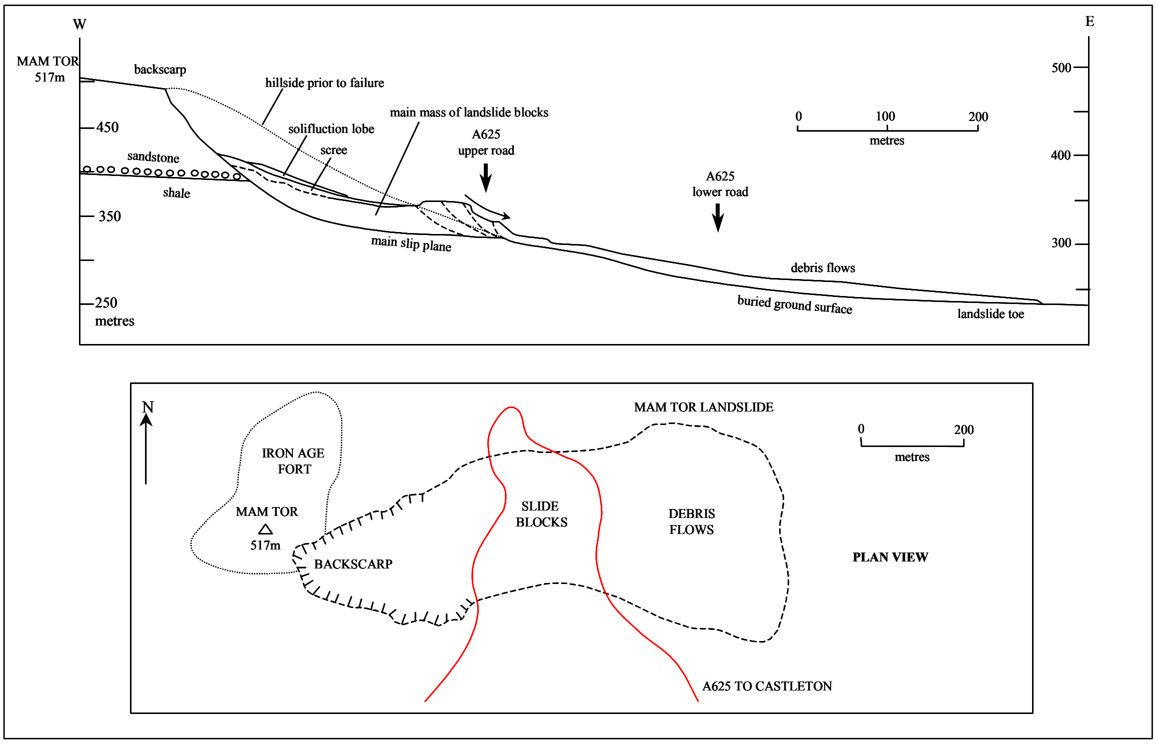


Figure 12 Schematic diagram of the landslide at Mam Tor

Figure 13 **Recent landslides at Cain's Folly, Dorset 28th December 2000**
Photo, Nick Gregory © Apex

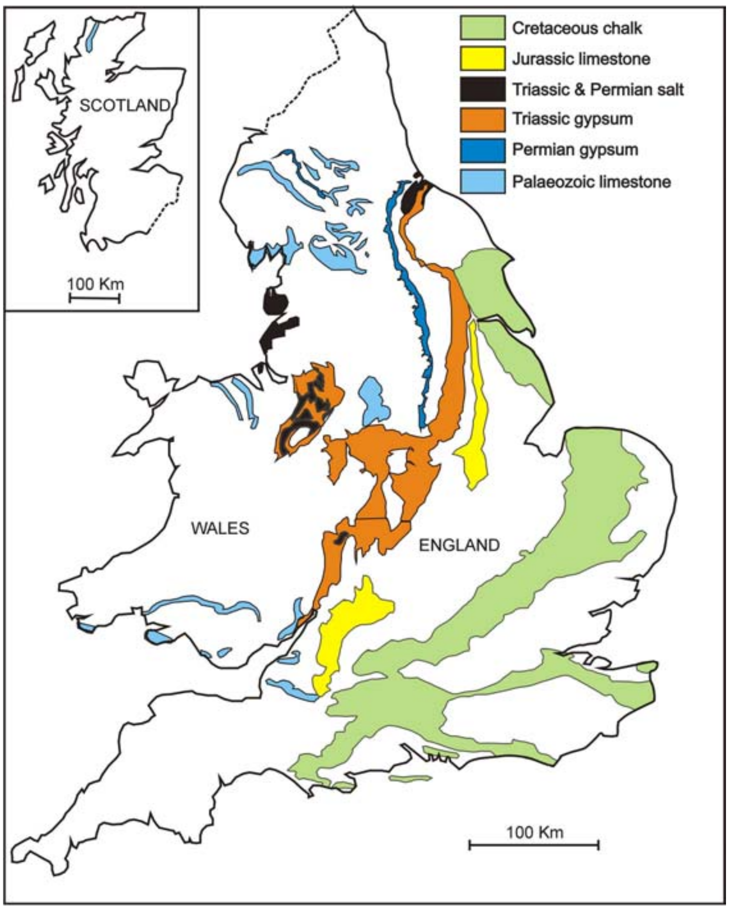


Figure 14 Location of UK karst regions

Figure 15 Sliced stalagmite showing variation in growth rates over time
Photo, A.R. Farrant © NERC

Figure 16 Hells Kettles near Croft south of Darlington

Natural water-filled subsidence hollows caused by underground dissolution of Permian gypsum. This site is an SSSI with a unique pond flora dependent on the sulphate and carbonate-rich spring water that flows from the pond. The temperature of the groundwater means that the pond rarely freezes and in the winter it steams. One of the ponds here is reported to have formed by a dramatic collapse in 1179. Its legend as a bottomless pit may have influenced Lewis Carroll, who lived nearby at Croft Rectory, to write the story of “Alice in Wonderland”. Photo A.H.Cooper © NERC

Figure 17 Karst scenery at Malham © NERC

Figure 18 Solution collapse, affecting properties at Ripon
Photo A. H. Cooper © NERC

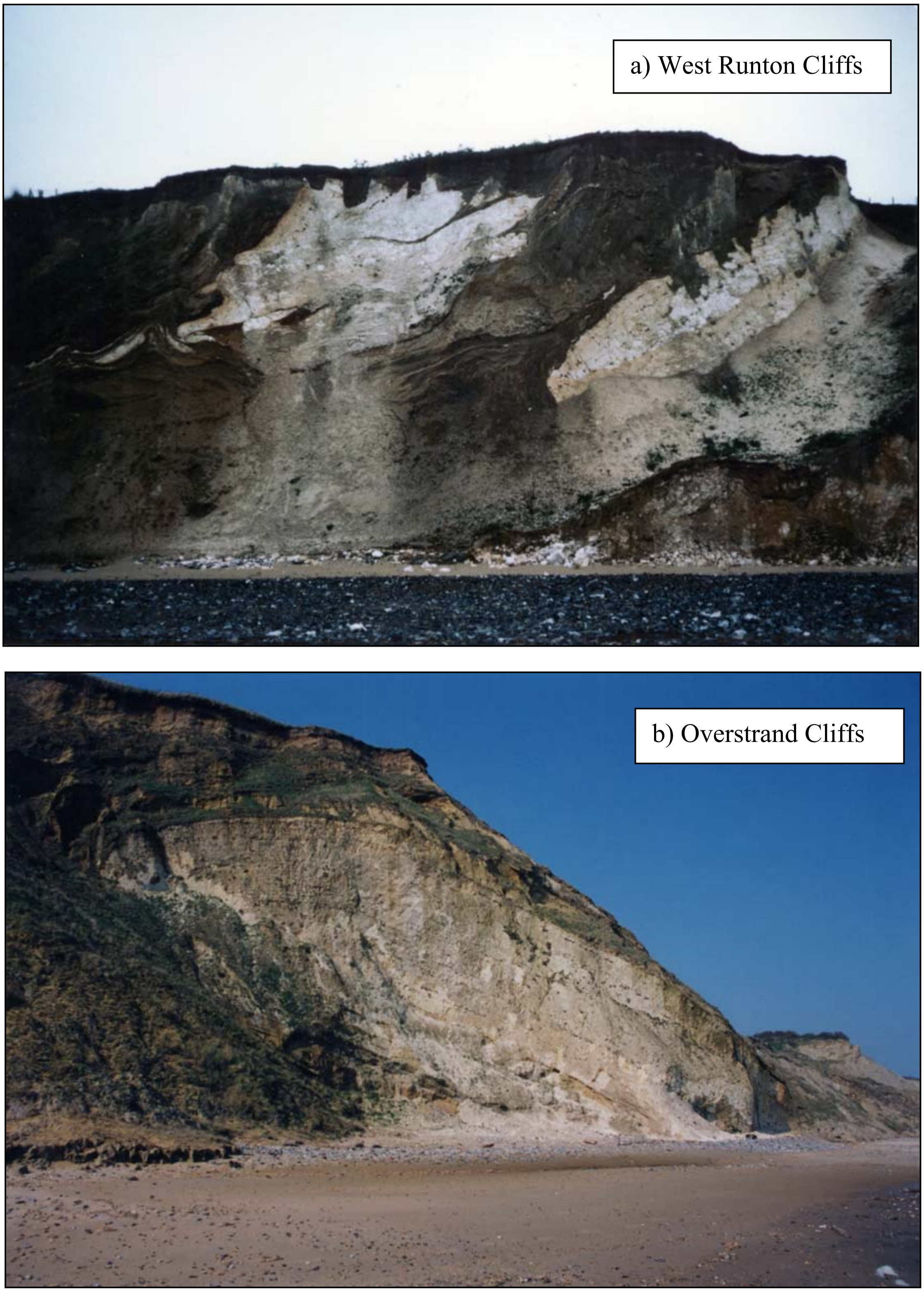


Figure 19 **Large blocks of Chalk pushed up into the glacial sediments by the action of an ice sheet, West Runton cliffs (a) and Overstrand cliffs (b), Norfolk**. Photo a) B. Humphreys b) D. Tragheim © NERC

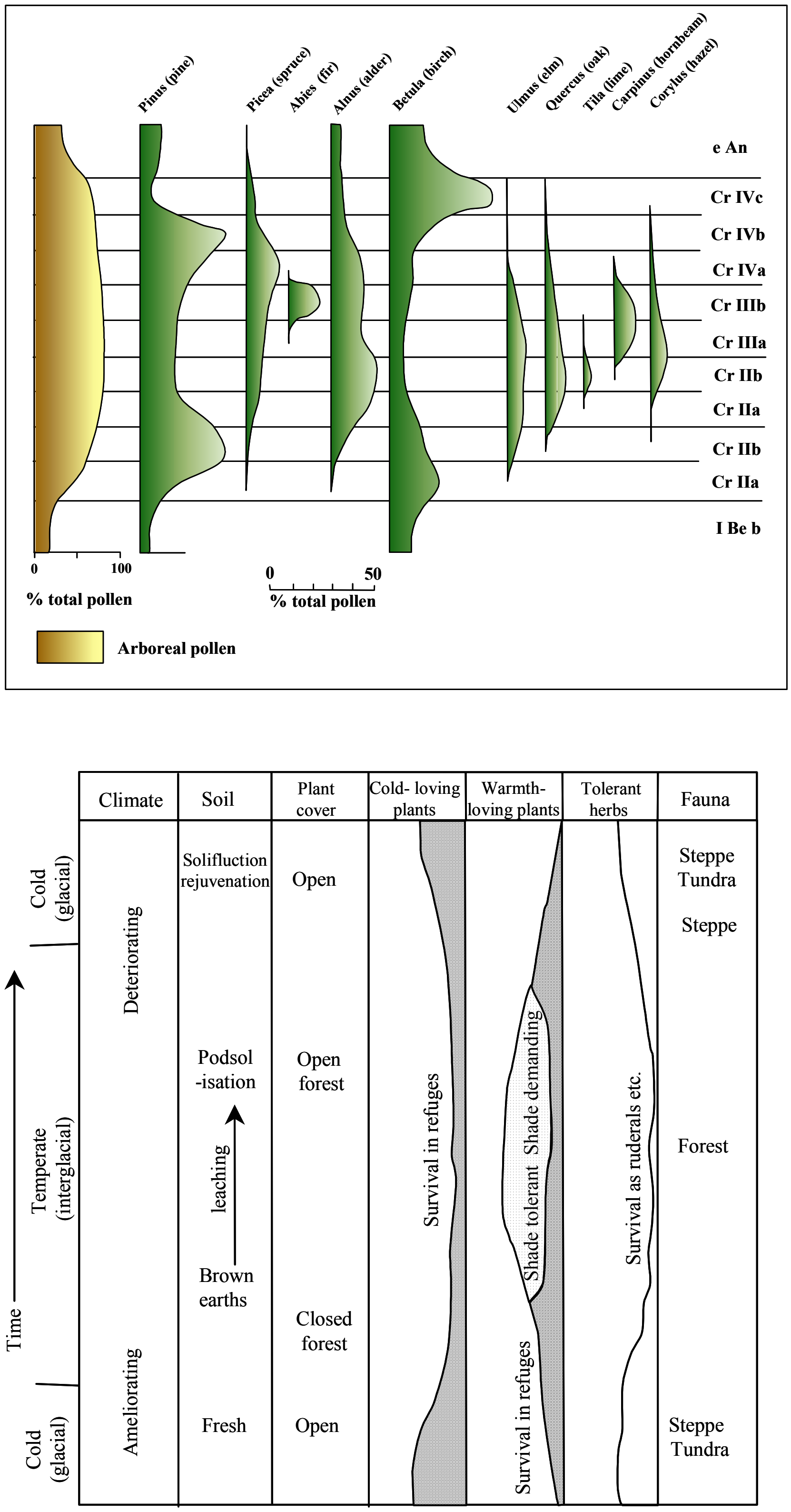


Figure 20 Pollen diagram from Norfolk glacial deposits preserving a record of changing vegetation and climate

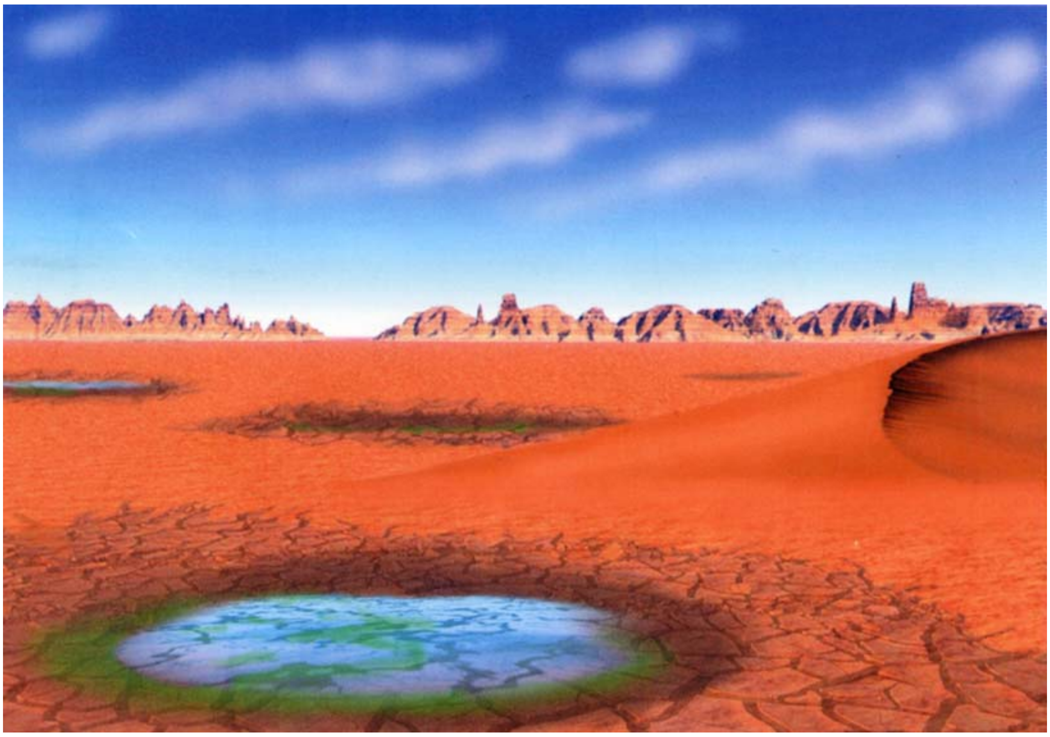


Figure 21   Triassic desert environment

During much of the Triassic Period, 250 million years ago, many parts of England experienced desert conditions and basked in a hot arid climate. The combination of arid conditions and windblown- shifting sand dunes created an environment in which few plants or animals could survive. However, occasional rainstorms transformed the normally barren and inhospitable desert plains and created temporary rivers and shallow lakes. These lakes supported a restricted number of burrowing worms and snails and specialised fish that were able to withstand long periods of drought when the water in the lakes evaporated. Around the margins of the lakes small moss like plants grew and survived until the lakes dried up. The reddish orange colour of the rocks is caused by the presence of iron-rich minerals that grew between individual sand grains under these harsh conditions. © NERC

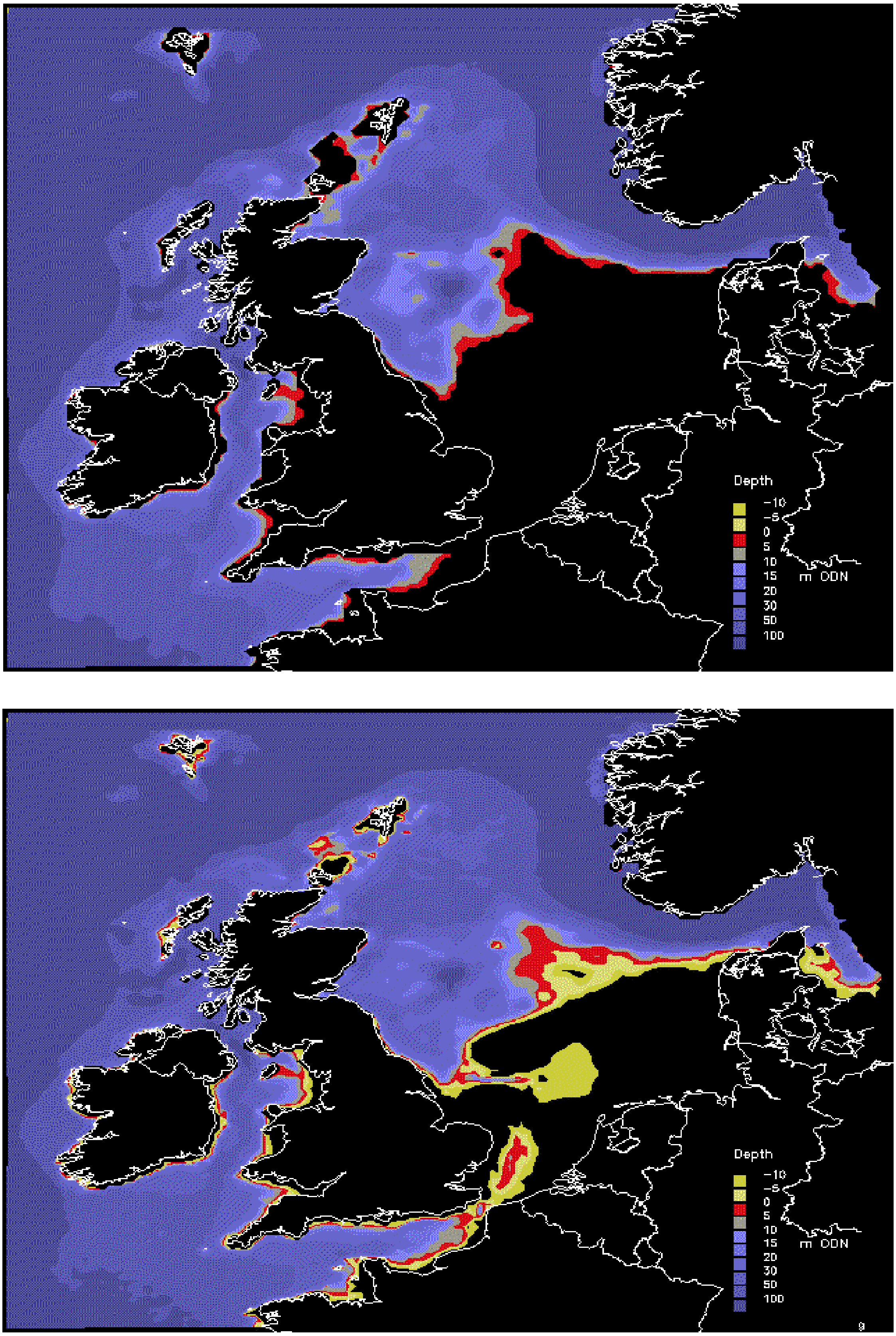


Figure 22 Reconstruction of sea level in the southern North Sea 10,000 and 9,000 years ago

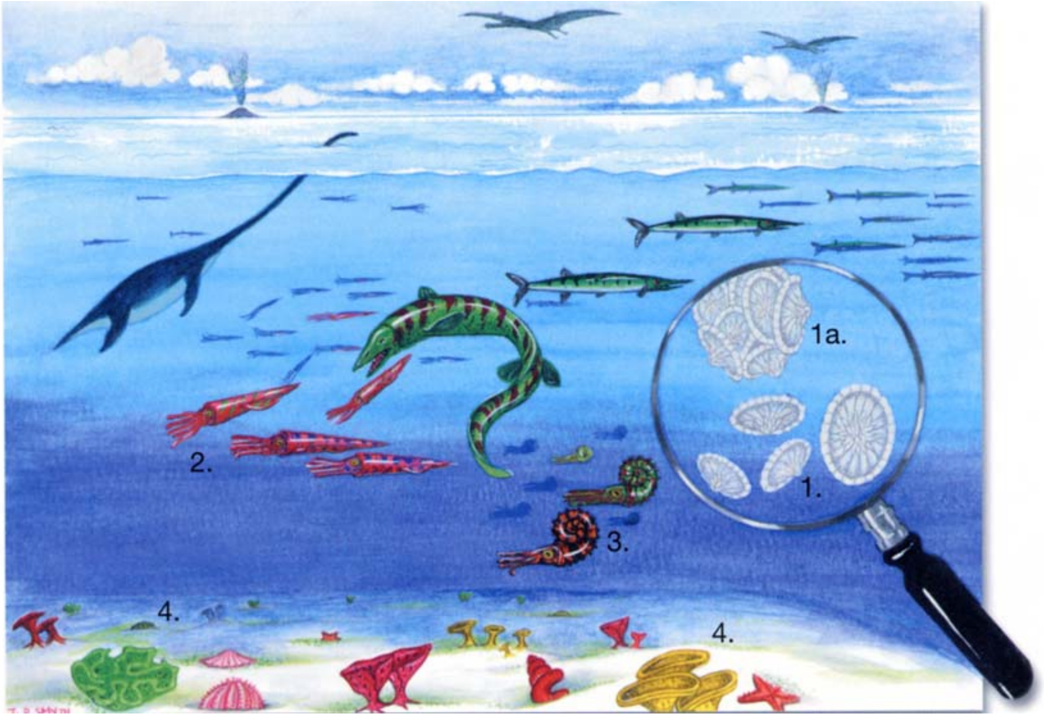


Figure 23 Reconstruction of the warm tropical Cretaceous seas

In late Cretaceous times, about 65-80 million years ago, warm seas covered much of England. Abundant and varied life forms flourished in the shallow waters. The white chalk rock that contains their fossilised remains is composed almost entirely of coccoliths (1). Made of the mineral calcite, they are the individual microscopic plates that covered and protected these tiny animals inside their coccosphere (1a). Other common fossils found in the chalk are belemnites (2) that probably resembled present day squid. Occasional examples of ammonites (3), related to the present day Nautilus, are found along with scales from fish that swam in the clear seas. The seabed was colonised by special animals, particularly sponges (4) that were able to anchor themselves to the soft white mud that was later changed into the chalk rock. At this time there is some evidence to indicate that distant volcanoes were erupting fine ash into the atmosphere that later fell into the sea. © NERC

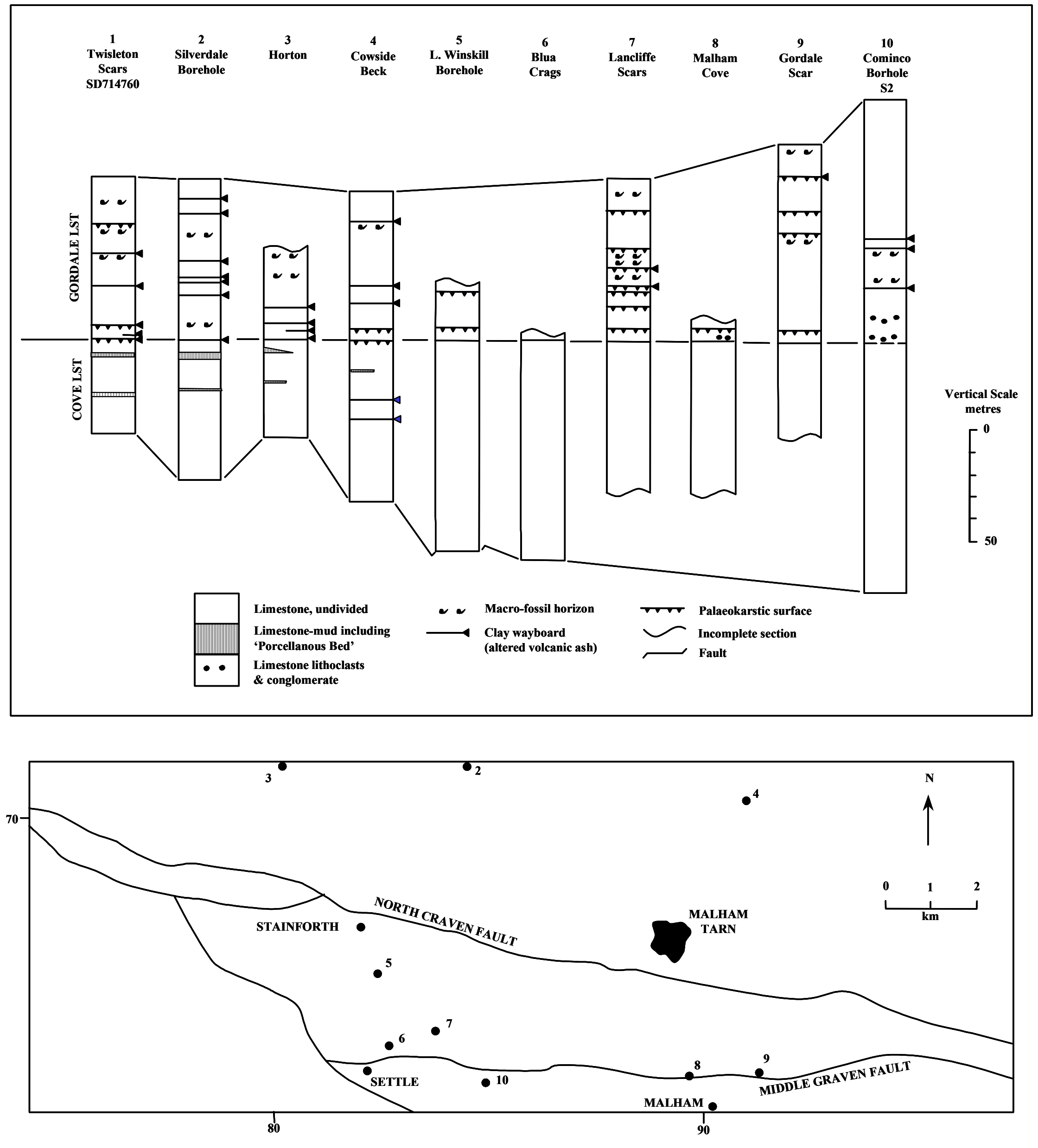


Figure 24 Frequency of palaeokarst emergent surfaces in the Carboniferous marine carbonate succession of the Malham area

Figure 25 Ash bands in the London Clay at Wrabness.
Photo H. J. Evans © NERC

Figure 26 Concertina folding in Devonian rocks at Crackington, Cornwall
Photo J. M. Pulsford © NERC

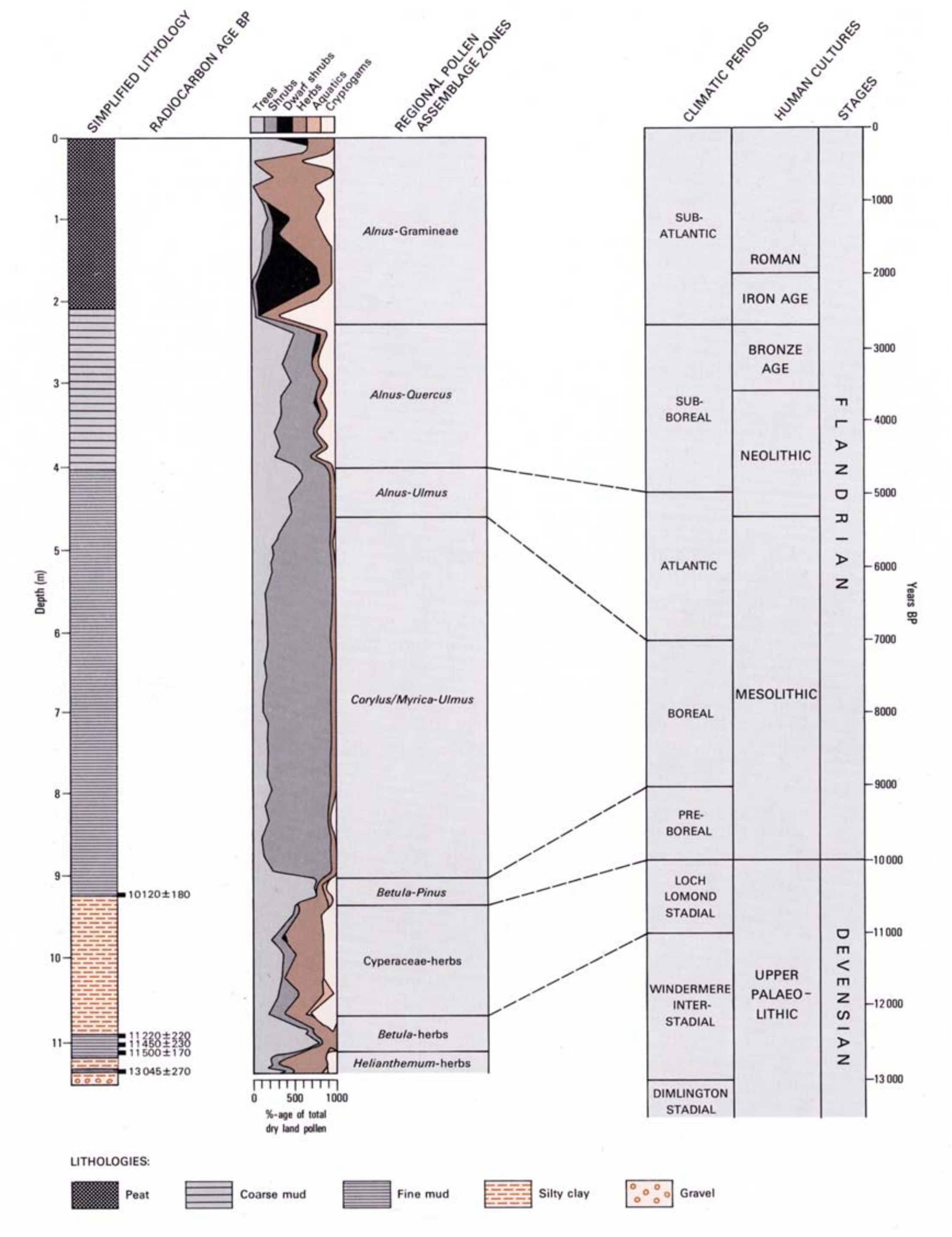


Figure 27 **Pollen analysis and radiocarbon dating of a cored succession from a Yorkshire lake.** © NERC