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Chapter 1 Introduction to Geological Hazards in the UK: Their Occurrence, Monitoring and Mitigation

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Abstract: The UK is perhaps unique globally in that it presents the full spectrum of geological time, stratigraphy and associated lithologies within its boundaries. With this wide range of geological assemblages comes a wide range of geological hazards, whether geophysical (earthquakes, effects of volcanic eruptions, tsunami, landslides), geotechnical (collapsible, compressible, liquefiable, shearing, swelling and shrinking soils), geochemical (dissolution, radon and methane gas hazards) or related to georesources (coal, chalk and other mineral extraction). An awareness of these hazards and the risks that they pose is a key requirement of the engineering geologist. This volume sets out to define and explain these geohazards, to detail their detection, monitoring and management, and to provide a basis for further research and understanding, all within a UK context.

1.1 Introduction

A geological hazard (geohazard) is the consequence of an adverse combination of geological processes and ground conditions, sometimes precipitated by anthropogenic activity. The term implies that the event is unexpected and likely to cause significant loss or harm. To understand geohazards and mitigate their effects, expertise is required in the key areas of engineering geology, hydrogeology, geotechnical engineering, risk management, communication and planning, supported by appropriate specialist knowledge of subjects such as seismology and volcanology. There is a temptation for geoscientists involved in geohazards to get too focused on the 'science' and lose sight of the purpose of the work, which is to facilitate the effective management and mitigation of the consequences of geohazards within society. The Geological Society considered that a Working Party Report would help to put the study and assessment of geohazards into the wider social context, helping the engineering geologist to better communicate the issues concerning geohazards in the UK to the client and the wider public.

1.2 A history of significant geohazards in the UK

At the risk of cultural misappropriation, people of the UK often sing of their 'green and pleasant land' in the misguided view that they are unaffected by major natural and geological hazard events that impact the rest of the world, as these all occur in far-off places that are a very long way from the shores of the UK. However, as a country, we possess the full geological spectrum of the stratigraphic column with its associated lithologies. It is hard to think of any geological assemblage that cannot be found within the British Isles with rocks dating from the Precambrian to the Quaternary along with examples of all major environments of deposition, formation and modification. The legacy of this assemblage and the associated geological hazards, whether geophysical, geotechnical, geochemical or related to georesources, are in evidence across the UK.

Impacts of more distal events can also be seen with the 2010 Icelandic Eyjafjallajökull volcanic eruption that demonstrated we are not immune from global active volcanic events; the economic impact of the ash cloud was felt through disruption to air travel. Further back in our more recent history, the 1783–1784 Icelandic Laki Fissure eruption with its toxic gas cloud saw a significant mortality crisis across the UK with as many as 23 000 British people dying from the poisoning (Grattan & Brayshay 1995). The possibility of a caldera-collapse super-volcanic event centred on the Campi Flegrei in Italy cannot be ruled out in the immediate or distant future, with a significant impact on mainland Europe, north Africa and the UK.

The UK has the potential to be harmed by the full remit of documented geological hazards ranging from earthquakes, tsunami and landslides to the significant effects of clay particles that shrink and swell with moisture.

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The impact of geological hazards can be measured in terms of fatalities, landscape loss and economic impact. The tragedy of Aberfan, South Wales, exacerbated by the number of children in the overall death toll, is perhaps the most significant hazard event of modern times affecting the UK, although the impact of a future Lisbon-style earthquake and associated tsunami or Storegga-generated tsunami on the UK may well present our greatest geological hazard challenge.

In the writing of this introduction to *Geological Hazards in the UK*, expert opinion was canvassed as to which geological hazards impacting the UK in our recent geological history could be considered as the most noteworthy. The list is both specific (to individual events) and generic (to more widely impacting geohazards such as subsidence related to coal mining). The following sections (presented alphabetically) represent impacts in terms of fatalities, as well as economic and social effects.

1.2.1 Gas hazards

1.2.1.1 1986 Loscoe methane gas explosion, Derbyshire
Loscoe was the site of a landfill gas migration explosion on 24 March 1986. There were no fatalities, but one house was completely destroyed by the blast. Atmospheric pressure on the night of the explosion fell 29 mbar over a 7-hour period, drawing methane through a permeable sandstone horizon from a former landfill site (Fig. 1.1). Landfill gas collected under the ground near the house at 51 Clarke Avenue, entered the house and ignited with catastrophic effects (Williams & Aitkenhead 1991).

1.2.1.2 Radon hazard, Northamptonshire
Radon is a naturally occurring odourless, colourless radioactive gas that migrates into homes through floors and walls and is the major source of ionizing radiation exposure of the UK population. High levels of radiation have been associated with an increased incidence of lung cancer, particularly when its exposure is long term and combined with cigarette smoking. Radon is more prevalent in some areas of the country than others and Northamptonshire, with a specific Jurassic bedrock lithology, has high levels of the gas emitted into the atmosphere. Remedial action and preventative measures are necessary for house construction in these affected areas (Sutherland Sharman 1996).

1.2.2 Karst and dissolution hazard

1.2.2.1 2012 Carsington Pasture, variable rockhead, Derbyshire
Excavation of the foundations of four wind turbines at Carsington Pasture exposed buried, sediment-filled hollows in the bedrock that had formed as the result of karstification. The bedrock geology comprised dolomitized Carboniferous limestones that had been subject to lead-zinc-barite mineralization. Excavation of the foundations commenced on 8 May 2012. Difficult ground conditions were encountered that necessitated remedial engineering measures and delayed the project by 12–14 months, with consequent economic impacts (Czerewko *et al.* 2015; Raines *et al.* 2015).

1.2.2.2 Ripon dissolution subsidence, North Yorkshire
The area in and around Ripon is significantly affected by the presence of gypsum, hydrated calcium sulphate ($CaSO_4 \cdot 2H_2O$), in the local Permo-Triassic bedrock. A substantial number of sinkholes have developed in the area caused by the dissolution of the gypsum and the formation of gypsum karst. Subsequent collapse of these features (Fig. 1.2) has

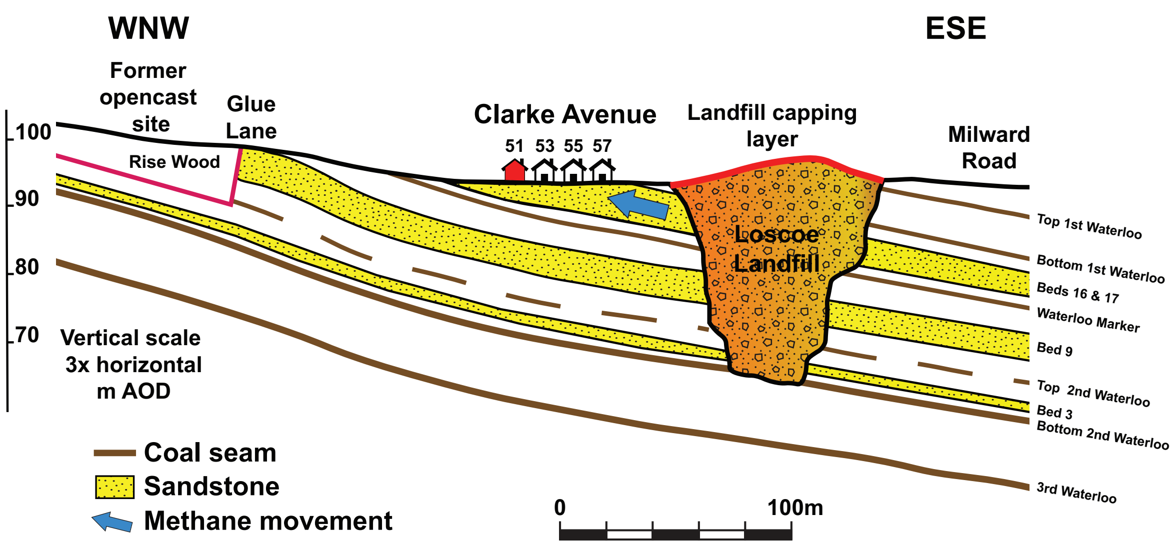

Fig. 1.1. Geological cross-section through the Loscoe landfill (Williams & Aitkenhead 1991).

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Fig. 1.2. Sinkhole development near Ure Bank Terrace, Ripon, North Yorkshire (photo credit: David Giles).

led to considerable structural damage to buildings in the city (Cooper 2007).

1.2.3 Landslides and slope failures

1.2.3.1 Significant inland landslides

There are many examples of significant inland landslides that could be included here with specific events, considered as key geohazards, affecting infrastructure and other valuable assets. Such examples include: Jackfield, Shropshire 1952 (Henkel & Skempton 1955); Buildwas, Shropshire 1773 (Pennington 2008); A85 road, Glen Ogle, Lochearnhead, Stirlingshire (Winter *et al.* 2006); Hatfield Main Colliery 2013, South Yorkshire (BGS n.d.); Rest and be Thankful Pass, A83, Argyll and Bute 2007, 2009, 2011, 2012 (Wong & Winter 2018); Bournville and East Pentwyn, Blaina (Siddle 2000); Taren, Taff Valley (Cobb 2000); Castle Hill, Cheriton, Kent (Griffiths *et al.* 1995). The most noteworthy case histories are described below.

1.2.3.2 1966 Aberfan tip failure, South Wales

The catastrophic collapse of a colliery spoil tip, created on the hillslope above the village of Aberfan, occurred on 21 October 1966 (Fig. 1.3). Significantly, the tip overlaid a natural spring that fed water into the colliery spoil. The tip was further destabilized by a period of heavy rain eventually leading to a devastating mudflow, killing 116 children and 28 adults as it engulfed the local junior school and other buildings (Tribunal Appointed to Inquire into the Disaster at Aberfan on October 21st 1966).

1.2.3.3 2000 M25 Flint Hall Farm landslide

On 19 December 2000, during one of the wettest UK winters on record, a 200 m long section of the Flint Hall Farm cutting on the M25 failed and threatened to close the motorway, which carries over 120 000 vehicles a day (Fig. 1.4). Further rainfall triggered additional movements during January and early February 2001, further threatening the carriageway (Davies *et al.* 2003; Griffiths & Giles 2017).

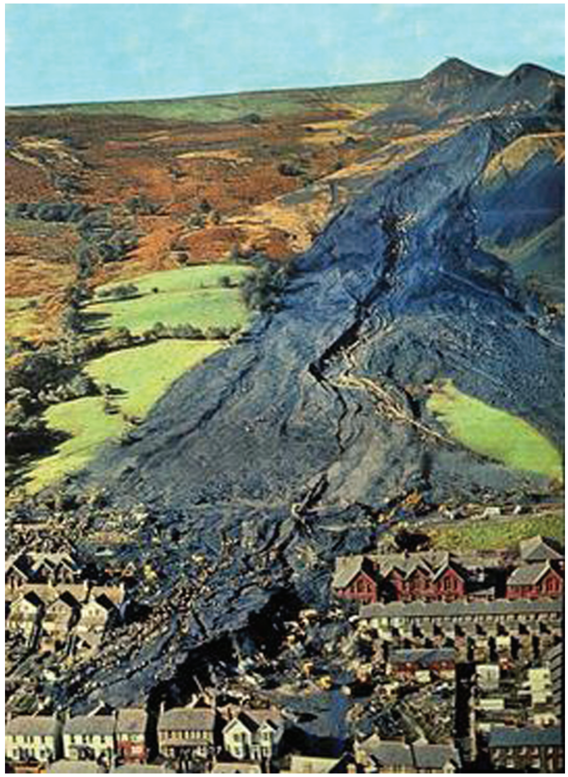

Fig. 1.3. Aberfan in the days immediately after the disaster, showing the extent of the spoil slip (https://en.wikipedia.org/w/index.php?curid=54882575).

1.2.3.4 1979 Mam Tor landslide, Derbyshire

The landslide at Mam Tor was probably initiated by the erosive steepening of valley slopes during periods of high

Fig. 1.4. Flint Hall Farm site works impacted on M25 carriageway (Griffiths & Giles 2017).

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Fig. 1.5. Damage to the A625 carriageway by the Mam Tor landslide, Derbyshire (photo credit: David Giles).

rainfall and freeze–thaw action during the Devensian. The landslide was the subject of intensive investigations due to the damage that the slope instability was causing to the A625 road that traversed the landslide's displaced material (Fig. 1.5). The road has been closed since 1979 (Waltham & Dixon 2000; Griffiths & Giles 2017).

1.2.3.5 Coastal landslides and coastal erosion

The UK coastline has always been prone to erosion and major landslide events, affecting both property and land. Classic examples include the Undercliff, Isle of Wight (e.g. Moore *et al.* 2010), Happisburgh, Norfolk (e.g. Poulton *et al.* 2006) (Fig. 1.6), Black Ven, Dorset (e.g. Brunsden & Chandler 1996), Fairlight Glen, East Sussex (e.g. Moore 1986; Moore & McInnes 2011), where each location is influenced by the site-specific lithologies present.

1.2.3.6 1915 Folkestone Warren landslide, Kent

The Folkestone Warren landslide is one of the largest on the English coast and is a classic example of a deep-seated

Fig. 1.6. Erosion on the North Norfolk coast, an example from Happisburgh (photo credit: David Giles).

Fig. 1.7. Landslide at Folkestone Warren, Kent, 1914 (photo credit: Network Rail).

multiple retrogressive, compound mechanism, having translational, rotational and graben features. A major reactivation occurred throughout the complex in 1915 (Fig. 1.7), seriously disrupting the railway constructed in 1844 (British Geological Survey n.d.; Hutchinson 1969, 1988; Hutchinson *et al.* 1980; Trenter & Warren 1996; Warren & Palmer 2000).

1.2.3.7 1983 Holbeck Hall landslide, Scarborough, Yorkshire

The Holbeck Hall landslide destroyed the Holbeck Hall Hotel between the night of 3 June and 5 June 1993 (Fig. 1.8). A rotational landslide developing into a flow involving *c.* 1 Mt of glacial till cut back the 60 m high cliff by 70 m. It flowed across the beach to form a semi-circular promontory 200 m wide, projecting 135 m outwards from the foot of the

Fig. 1.8. Landslide at Holbeck Hall, Scarborough, Yorkshire, 1983 (photo credit: British Geological Survey).

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Fig. 1.9. Carsington embankment under construction in 1984 (photo credit: Winter *et al.* 2017).

cliff. The likely cause of the landslide was a combination of rainfall (140 mm in the 2 months before the failure took place), issues related to slope drainage and porewater pressure build-up in the slope, all influenced by the site geology (British Geological Survey n.d.; Forster 1993; Lee 1999; Forster & Culshaw 2004).

1.2.4 Periglacial legacy

1.2.4.1 1984 Carsington Dam embankment failure, Derbyshire

An embankment dam was to be constructed 3 km south of Carsington (Fig. 1.9). An extensive ground investigation was carried out, but failed to recognize relict periglacial features that were present in the ground profile. Consequently, the embankment failed during construction in June 1984 and then had to be demolished and rebuilt to a design based on the correctly understood ground conditions. The reconstruction was successfully completed, but at a considerable cost and delay. The finished reservoir opened in 1992 (Skempton & Vaughan 2009; Martin *et al.* 2017).

1.2.5 Central London, drift-filled hollows

Engineering works carried out in central London over many decades have revealed a number of buried hollows that exhibit curious characteristics (Fig. 1.10). Some extend deep into the bedrock geology and are infilled with disturbed superficial deposits and reworked bedrock. Others are contained within the superficial deposits. The buried hollows can be up to 500 m wide and more than 60 m in depth. As the infill material often has different behavioural characteristics from the surrounding deposits, failure to identify them during an initial site investigation can prove costly. Much work has been undertaken in London to further delineate the presence of these anomalous depressions in the London Clay. Various modes of formations of these features have been proposed, including simple scour, dissolution of the underlying chalk, valley bulging, frost heave, former ice wedges or thermokarst processes, or it has even been proposed that they are former pingo remnants (Banks *et al.* 2015; Toms *et al.* 2016; Griffiths & Giles 2017).

1.2.5.1 1965 A21 Sevenoaks Bypass slope failures, Kent

The slope failures that occurred in 1965 during the construction of the Sevenoaks Bypass in Kent led to a new understanding of the behaviour and geotechnical properties of clay slopes. The failures occurred in the natural ground that had been affected by periglacial conditions during the Quaternary. Originally described as relict solifluction lobes (and now thought to be remnants of active-layer detachment slides with underlying solifluction sheets), these were reactivated during the construction works leading to considerable delays with the project and eventually a new road alignment being developed (Weeks 1969; Martin *et al.* 2017) (Fig. 1.11).

1.2.5.2 1961 M6 Walton's Wood embankment failure

The embankment failure at Walton's Wood in Staffordshire during the construction of the M6 is a seminal case study in engineering geology. Soon after the beginning of construction of an embankment, a failure occurred through the reactivation of an undetected relict landslide with movement along pre-existing shear surfaces (Fig. 1.12). The subsequent field and laboratory investigations led to major advances in the understanding of residual strength within clay slopes (Early & Skempton 1972; Griffiths & Giles 2017).

1.2.6 Seismic events

1.2.6.1 1884 Colchester earthquake, Essex

This earthquake occurred on 22 April 1884 and caused considerable damage in Colchester and surrounding villages in Essex. In terms of overall destruction (intensity), it can be considered the most destructive earthquake to have hit the UK and was estimated as a local magnitude (M_L) 4.6 event (Haining 1991).

1.2.6.2 1931 Dogger Bank earthquake, North Sea

This M_L 6.1 event, with a Modified Mercalli intensity of VI (strong) to VII (very strong), was the largest-magnitude earthquake recorded in the UK since measurements began. The epicentre in the North Sea meant that damage was significantly less than it would have been on the UK mainland (Versey 1939; Musson 2007).

1.2.7 Tsunami events

1.2.7.1 1755 Lisbon earthquake-generated tsunami

The largest historically recorded seismic event in Europe is considered to be the 1755 Lisbon earthquake, estimated as an M_s 8.5 magnitude (possibly M_w 9.0) event and between X and XI Modified Mercalli intensity scale. The impacts in the UK resulting from the earthquake and subsequent tsunami were first noted with reports of seiche (standing waves in an

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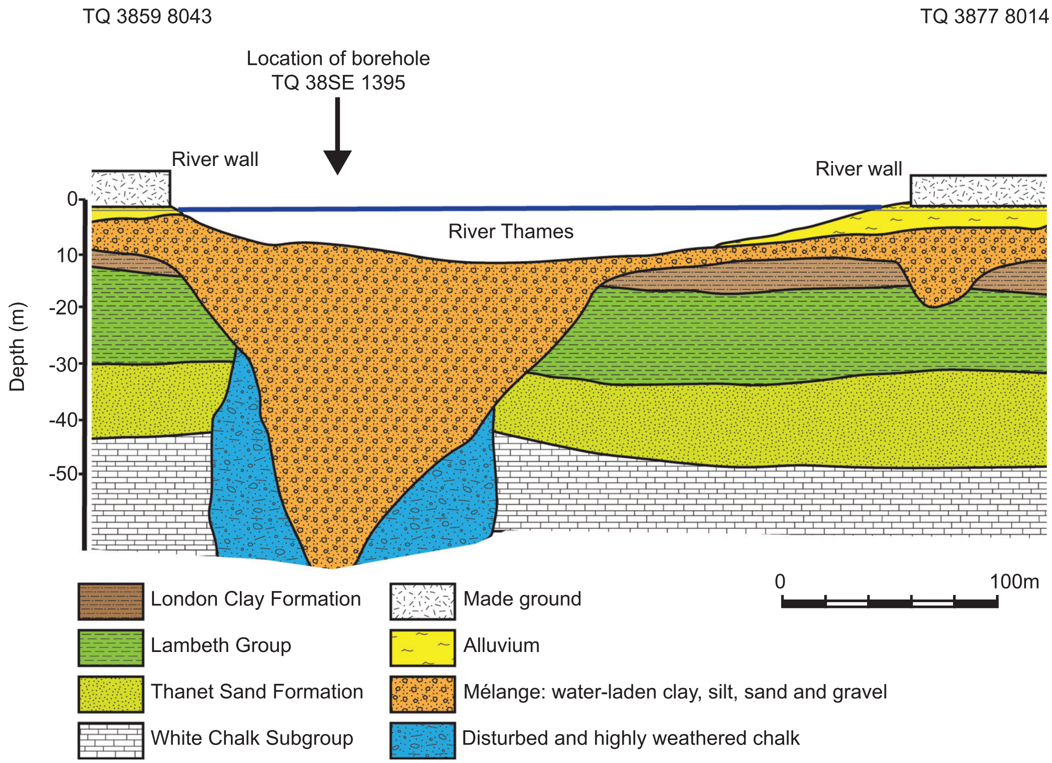

Fig. 1.10. Cross-section through a drift-filled hollow, Blackwall Tunnel, London (Griffiths & Giles 2017).

enclosed or partially enclosed body of water) in various harbours, lakes and ponds across the country. In the SW, wave trains were also reported with noticeable sea-level variations over several hours. Lisbon-related tsunami deposits have also been identified in parts of SW England (Giles 2020*b*).

1.2.7.2 c. 8150 BP Storegga submarine landslide and tsunami

Along the eastern and northern coasts of Scotland and at locations in NE England, sites have been investigated where a continuous layer of marine sediments can be identified. These sediments have been interpreted as tsunami deposits and have been attributed to a major submarine landslide event that displaced approximately 3500 km^3 of sediment along the mid-Norwegian margin of the North Sea (Fig. 1.13). Recent work has suggested that the occurrence of landslides with tsunami-generating potential may be more frequent, which has significant implications for the associated tsunami threat to the UK and Norwegian coasts (Giles 2020*b*).

1.2.8 Volcanic events

1.2.8.1 2010 Eyjafjallajökull ash fall disruption

Although relatively small for volcanic eruptions (rated 1 on the volcanic explosivity index), the 2010 eruptions of Eyjafjallajökull caused enormous disruption to air travel across western and northern Europe; around 20 countries, including Britain, closed or restricted their airspace to commercial jet traffic, affecting approximately 10 million travellers (Fig. 1.14). The restriction of UK airspace affected some 600 000 people (Gudmundsson *et al.* 2012).

1.2.8.2 1783–1784 Laki fissure eruption, Iceland

The 1783 Laki eruption lasted 8 months, during which time about 14 km^3 of basaltic lavas were erupted. Haze from the eruption was reported globally. An estimated 80 Mt of sulphuric acid aerosol was released by the eruption, known to be the largest air pollution incident in historic times. August temperatures in the UK in 1783 were 2.5–3°C higher than the decadal average, causing the hottest summer on record for 200 years. A bitterly cold winter followed with temperatures 2°C below average. An acid fog persisted over much of Europe, causing to an increase in sickness levels. In England, the period July 1783 to June 1784 is classified as a ‘mortality crisis’, with the death rate increasing by 30 000 (i.e. doubling) (Witham & Oppenheimer 2004).

1.2.9 Mining hazards

1.2.9.1 2000 chalk mine collapse, Reading, Berkshire

In January 2000, several cavities of a nineteenth century chalk mine collapsed causing major subsidence of the

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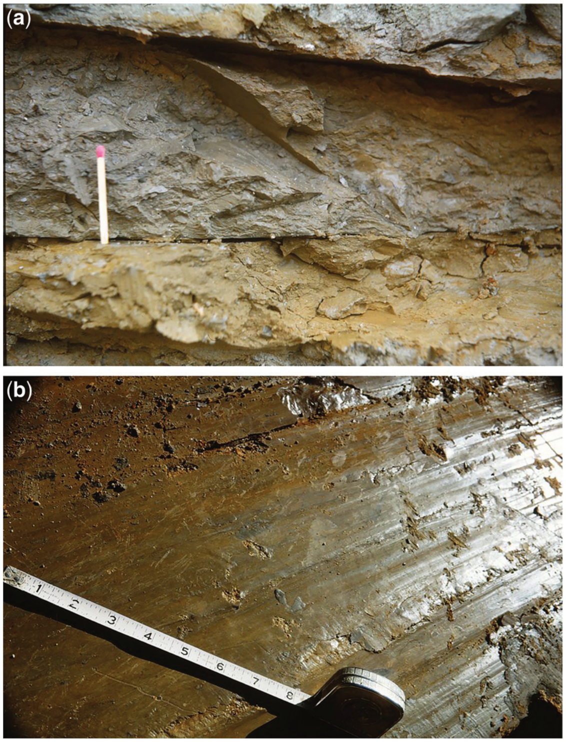

Fig. 1.11. Sevenoaks bypass: (**a**) shear surfaces; and (**b**) polished shear surface (Martin *et al.* 2017).

overlying ground around the Field Road (Fig. 1.15) and Coley Road areas in Reading. Thirty homes were immediately evacuated for residents' safety, with two homes later collapsing. The mines were remediated over a 12-year period to fill the underground mine network using 1742 t of grout, costing approximately £4.3 million (Edmonds 2008; Terra Firma 2017).

1.2.10 Deep coal workings

1.2.10.1 1945 Ludovic Berry and Dolly the train incident, Wigan

There are numerous examples of hazards related to deep mines across the UK, and a notable accident associated with the coal mining industry occurred on 30 April 1945 (Fig. 1.16). *Dolly* was an engine that shunted coal wagons between the Maypole and Mains collieries in Wigan, driven by Mr Ludovic Berry. On the day of the accident, a large hole appeared in the ground under the railway lines between Abram and Platt Bridge. With the lines now unsupported they failed under the weight of the first wagons, causing them to plummet into the ground, taking the remaining wagons and Dolly with them. Ludovic, who tried to save the engine until it was too late to jump, lost his life. The hole had occurred as a result of the subsidence of a shaft sunk 60 years previously and sealed in 1932. The subsidence may have been the result of heavy rains in an area with many mine workings close by (Winstanley n.d.; K. Nicholls, pers. comm., 2019).

1.2.11 Geotechnical hazards

1.2.11.1 1976 subsidence related to clay shrinkage

Although clay shrinkage subsidence has damaged properties in the UK for hundreds of years, up until 1971 insurers did not consider it and domestic policies offered no cover. In 1971 insurance companies started to add subsidence cover to household policies, and the long hot summer of 1976 saw the first surge of subsidence claims. Many properties were affected by subsidence caused by clay shrinkage that proved

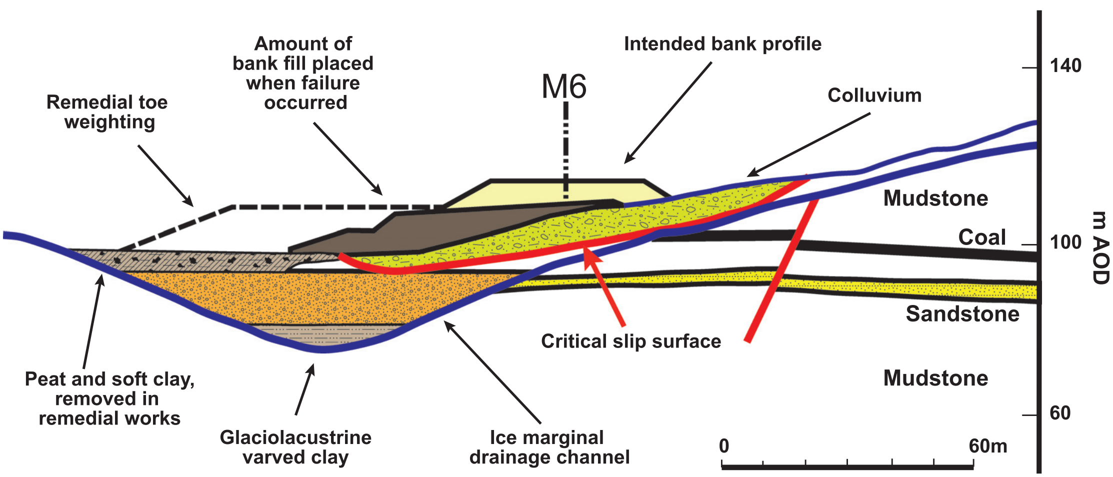

Fig. 1.12. Cross-section of the failed section of the M6 construction works, Walton's Wood, Staffordshire (Martin *et al.* 2017).

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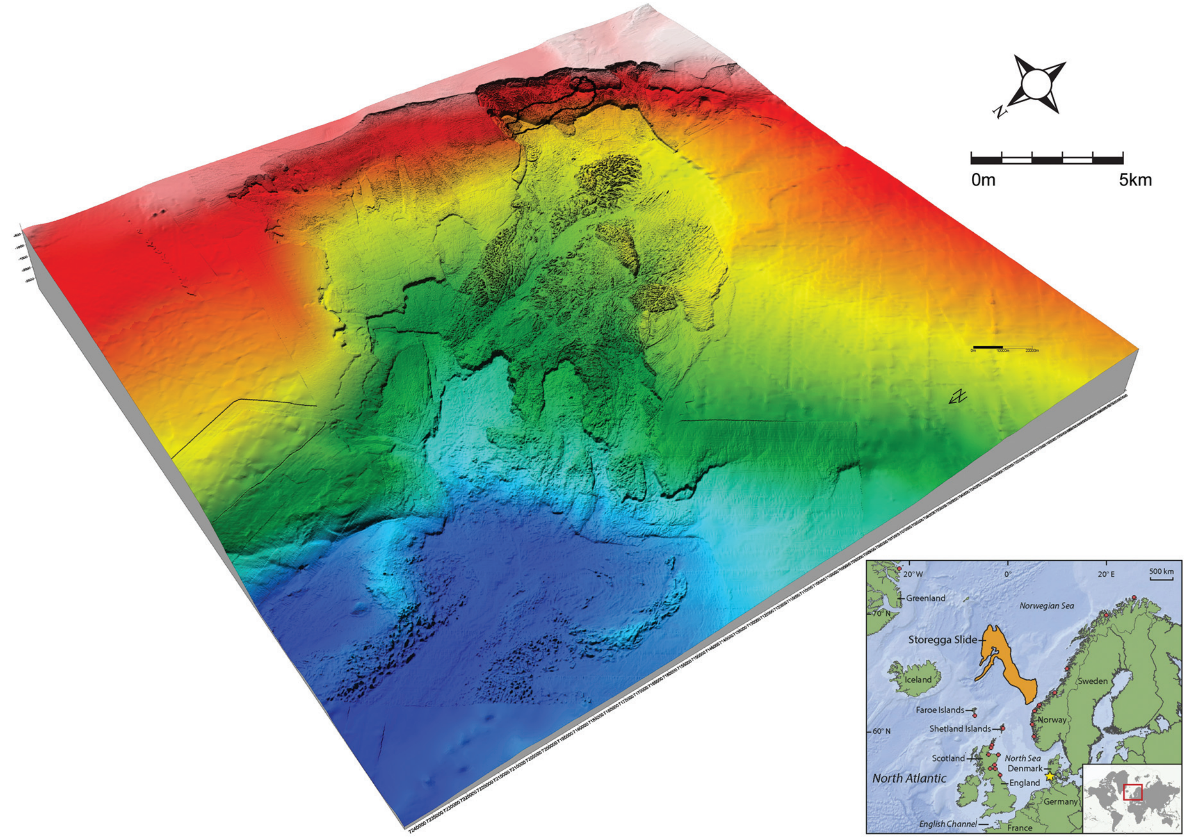

Fig. 1.13. Areal extent of the submarine Storegga landslide complex (Giles 2020*b*).

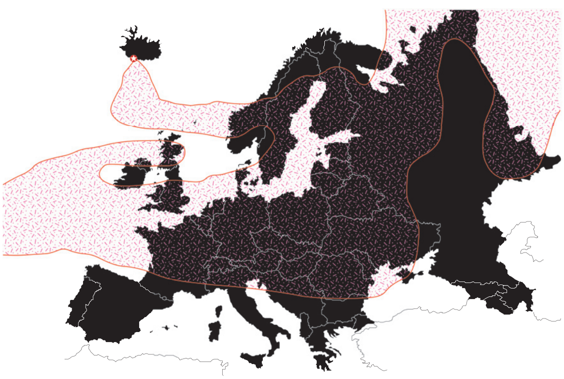

Fig. 1.14. Indicative map of the volcanic ash cloud (with Eyjafjallajökull volcano in red) spanning 14–25 April 2010, based on data available from the website of the London Volcanic Ash Advisory Centre (https://en.wikipedia.org/wiki/Air_travel_disruption_after_the_2010_Eyjafjallaj%C3%B6kull_eruption#/media/File:Eyjafjallaj%C3%B6kull_volcanic_ash_composite.png).

Fig. 1.15. Major subsidence through chalk mine crown hole collapse, Field Road, Reading, Berkshire (photo credit: Clive Edmonds).

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Fig. 1.16. The Crooked House, Dudley, suffering from coal mining subsidence.

to be both unexpected and very expensive for the insurance industry. Further surge events occurred in 1985, 1990, 1992, 1995, 1996, 2003 and 2006. Individual surge years regularly resulted in 50 000 subsidence claims and repair bills exceeding £400 million, with over £14 billion spent during the last four decades (Giles n.d.).

1.2.12 Poorly recognized geohazards

While dramatic and dynamic geohazard events perhaps always attract media attention, there are a substantial number of more mundane static and geotechnical geohazards that have had some substantial impacts to engineering projects. Subsurface boulders (e.g. Skipper *et al.* 2005), cemented layers (e.g. Newman 2009), running sands (Newman 2009), deoxygenation (e.g. Newman *et al.* 2013), and perched water tables (e.g. Toms *et al.* 2016) can cause massive problems related to ground engineering, even when well understood and characterized.

1.3 Geological Society Engineering Group Working Party on Geohazards

1.3.1 Background

The original Geological Society Working Party on Geohazards was initiated under the leadership of Professor Mike Rosenbaum, Dr David Entwistle and Dr Alan Forster in August 2002 following informal meetings held at the British Geological Survey, Keyworth. Due to many membership changes, the Working Group was reformatted in 2010 with a view to developing a web-based resource as opposed to a hardcopy book. This initiative again stalled with the final outcome of the Working Party being a series of themed chapters compiled remotely of any formal meetings. This Engineering Geology Special Publication represents the results of this long endeavour.

1.3.2 Membership

The Working Party was developed with a UK focus, but included a global perspective in the consideration of examples of good practice and the nature of geohazard issues of a generic nature. The following principal members served as chapter lead authors in this volume: Dr David Giles (Chair & Editor; Card Geotechnics Ltd), Professor Jim Griffiths (Editor; University of Plymouth), Professor Roger Musson (British Geological Survey), Dr Mark Lee (Ebor Geoscience), Professor Mike Winter (TRL Scotland), Professor Martin Culshaw (British Geological Survey), Dr Lee Jones (British Geological Survey), Professor Jeff Warburton (Durham University), Mr Tom Berry (Jacobs), Dr Laurance Donnelly (AHK), Dr Clive Edmonds (Peter Brett Associates), Mr Barry Gamble (independent consultant to UNESCO), Dr Tony Cooper (British Geological Survey), Dr Don Appleton (British Geological Survey) and Mr Steve Wilson (EPG Ltd.).

1.3.3 Terms of reference of the Working Party

The aim of the Working Party is to help geoscientists communicate the interaction of geohazards with society.

Our objectives are to: improve awareness and understanding of geohazards, and to assist in the definition of the role of the engineering geologist in the identification, management and mitigation of hazards in the UK; improve communication between specialists, and between hazards practitioners and the wider community; consider the need for, and the form of, a strategy for the integration of geohazards studies into the planning and development process, and to define areas in which future research is needed; and summarize the current level of scientific understanding of geohazards (in terms of: types, magnitudes and frequencies; geographical locations; elements at risk in society; levels of vulnerability to the various hazards; geohazard recognition and hazard and risk evaluation; issues surrounding the dissemination of geohazard information; geohazard mitigation strategies; and future planning issues in the light of geohazards).

1.3.4 Developing the report

The proposed target audience of the Working Party are professionals who deal with geohazards and their effects, including civil engineers, planners, developers and government, as well as aid organizations. The Working Party Report will help to put the study and assessment of geohazards into the wider social context, helping the engineering geologist to better communicate the issues concerning geohazards to the client and the public. The aim is to provide the document of first choice when a geohazard occurs, able to orientate the enquirer as to 'How did this happen?', 'Where can I get help?', and 'What should I do?' This is somewhat different to the target readership of previous Working Party reports of the Engineering Group, orientated towards the specialist engineering geologist seeking a standardization of approach. The report focuses on: an outline of the nature of geohazards

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and their engineering consequences; a description of state-of-the-art techniques for the understanding of geohazards, and for assessing the levels of hazard and risk associated with them; a review of the range of users of geohazard information, including a consideration of strengths and weaknesses of the current position, recognizing that it is the communication of geohazards information and data that can be the most difficult part of any investigation; an account of the ways in which geohazard information is utilized within society, considering the social context and economic impact of geohazards; an examination of the potential ways in which existing and future geohazard information could/should be used and by whom; and a review of how best to communicate the information to non-geoscientists.

1.3.5 Contents and structure of the report

The Working Party Report sets out to provide an outline of the nature of the specific geohazard and its engineering consequences, in a UK context. The report provides a description of state-of-the-art techniques for the understanding of the geohazard and for assessing the levels of hazard and risk associated with it. Each section within the Special Publication sets out to summarize the character of the geohazard and considers the following topics with respect to the specific geohazard: what it is; where it might be found or occur; how to recognize it; how best to mitigate its effects; current strategies for engineering management (avoidance, prevention and mitigation); identifying actions following the occurrence of a geohazard; definitions and glossary; and data sources, essential references and further reading.

The report is structured in five sections, each addressing a variety of similarly themed hazards: Section A, Tectonic Hazards; Section B, Slope Stability Hazards; Section C, Problematic Ground and Geotechnical Hazards; Section D, Mining and Subsidence Hazards; and Section E, Gas Hazards.

1.3.6 Geological hazards: Working Party definitions and report limitations

An issue that all Geological Society working parties encounter is setting limits to the scope of their final report. In the Hot Deserts Working Party (Walker 2012), there were discussions on the definition of a ‘desert’ and initially whether or not cold and polar deserts should be part of the work. In the end, the Working Party decided to limit the scope to ‘hot deserts’ and climatic criteria were used to establish the spatial extent of these areas (Charman 2012). Within the Glacial and Periglacial Working Party (Griffiths & Martin 2017), the decision was made, after long debate (Martin *et al.* 2017), to limit the report only to the cold phases of the Quaternary, relict glacial and periglacial landforms and deposits, and specifically the conditions in the UK.

For the Geological Hazards Working Party, the spatial limit was identified from the outset as being the UK; however, when the Working Party was initiated, there was no universally agreed definition on what constituted a *geohazard*, beyond stating it was a geological source of danger. Culshaw (2018) provides the most comprehensive summary of the meaning and nature of geohazards. Quoting Nadim (2013), Culshaw (2018) defines ‘hazard’ as

> … an event, phenomenon, process, situation, or activity that may potentially be harmful to the affected population and damaging to society and the environment. A hazard is characterised by its location, magnitude, geometry, frequency, or probability or occurrence and other characteristics.

Culshaw (2018) divided geohazards into three main groups: primary natural geohazards, secondary natural hazards and geohazards caused by anthropogenic activity.

Primary natural geohazards are cyclical in occurrence. They affect regions and are controlled by regional geology. They are generally unpredictable, as the geological processes are not yet well enough understood; at present, they are almost impossible to prevent. Earthquakes and volcanoes fall into this category, as do climatic conditions; when low-frequency events occur, the effects can only be dealt with through disaster mitigation plans such as evacuation, disaster response and reconstruction.

Secondary natural hazards are often triggered by the primary natural hazards; they affect sites and districts, are controlled by the local geology and are partially predictable from an understanding of geological processes. They can be controlled to some degree, and are best mitigated by land-use planning, insurance and site-specific engineering measures. Landslides and dissolution fall into this category.

Geohazards caused by anthropogenic activity include extraction of minerals and its after-effects, surface or near-surface engineering activities that go wrong, changes to surface and subsurface water conditions, and placement of waste. These geohazards will have varying degrees of geological control, but all involve anthropogenic activity.

An alternative way of classifying natural hazards that cause disasters, of which geohazards represent a subset, is to look at the causative processes. Based on this approach, CRED (2015) divided natural disasters into six categories: geophysical (earthquakes, mass movements, volcanoes); hydrological (floods, landslides, wave action); meteorological (storms, extreme temperatures, fog); climatological (drought, glacial lake outburst, wildfire); biological (animal accident, epidemic, insect infestation); and extra-terrestrial (asteroid or meteorite impact, space weather).

Under this classification, geohazards would fall under geophysical and some hydrogeological processes.

Culshaw (2018) provides a more comprehensive breakdown of geohazards (Table 1.1) based on the controlling causative process, and subdivides them into geomorphological, geotechnical, hydrological or hydrogeological, geological, marine and artificial. From this classification it is apparent that many geohazards are not relevant to the UK, which was the primary concern of this Working Party Report. However, there are some geohazards identified in Table 1.1 that are found in the UK but have not been included in this report, and this comes back to the problem of setting limits

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Table 1.1. *Classification of geohazards according to Culshaw (2018)*

Process category	*Nature of the geohazard*
Geomorphological	Aeolian soils (loess); dissolution (karst, sinkholes etc.); erosion; desiccation; mass movement (snow avalanches, cambering, landslides, etc.); permafrost
Geotechnical	Acidity; collapsing soils; compressible soils; dispersive soils; expansive soils; quick clay; saline soils; residual soils
Hydrological or hydrogeological	Groundwater level change; floods
Geological	Earthquakes (all aspects of ground motion); fault movement; liquefaction; ground subsidence; surface rupture; tsunamis; volcanic eruptions; dome collapse; pyroclastic flows; lahars; debris flows and avalanches; lava flows; ash/tephra falls; large volcanic projectiles; volcanic gases
Marine	Coastal erosion; submarine landslides; fluid escape features (such as liquefaction); gas release (e.g. gas hydrates); scour; turbidity currents
Artificial	Acid mine drainage; artificial ground; brownfield sites; contamination; landfill; mining hazards of subsidence and collapse; pollution; unfilled, partially filled, and filled excavations and voids

to the scope of the final publication. Nevertheless, some of these warrant further discussion and explanation.

The main omission in the Working Party Report is the primary natural hazard of volcanicity, for the reason that the last active eruption in the UK took place between 60.5 and 55 Ma on the west coast of Scotland (Bell & Williamson 2002). However, there is one interesting present-day component of these eruptions; in the early Eocene deposits of East Anglia and the London Basin, there are very thin bentonite clay beds derived from chemically altered volcanic ash (King 2002). Bromhead (2013) speculated that these beds might be one of the factors controlling the occurrence of landslides in the London Clay Formation. In addition, as discussed above, the ash and gas generated by intermittent present-day volcanic activity in Iceland will continue to be a threat to air travel and air quality over the UK.

A mass movement process that is a UK geohazard but is not discussed in detail in this report is soil erosion. A 2006 report from the Parliamentary Office of Science and Technology (2006) stated that 2.2 Mt of topsoil was eroded annual in the UK, and over 17% of arable land showed signs of erosion. However, unlike countries that required terracing and other physical methods for reducing soil erosion, the main way to mitigate soil degradation in the UK is through better farming practice. Identifying appropriate changes in agricultural practice lay outside the remit of the Working Party.

One phenomenon that falls at the boundary between a geohazard and a meteorological hazard is snowfall and the potential for avalanches. The occurrence of snow is dependent on climate, and the UK is not renowned for copious amounts of snow. However, there is thriving skiing industry in Scotland, where avalanches do occur. Diggins (2018) reported that over the 10-year period from 2008/09 to 2017/18, a total of 21 people were killed by avalanches in the Scottish Highlands; over 200 avalanches occur in this area each year. However, this must be compared with the European Alps where, over the last four decades, about 100 people per year have lost their lives in avalanches (Techel *et al.* 2016). The loss of life in the UK from avalanches is similar and perhaps greater to that from landslides if the tragedy of Aberfan is excluded. It should also be noted that avalanches are not restricted to the Scottish Highlands. Indeed, the greatest loss of life in a single snow avalanche in the UK occurred in December 1836 in Lewes in East Sussex, when seven cottages were destroyed and eight people killed by the collapse of a snow corniche that had developed on a chalk cliff in the South Downs. The nineteenth century artist Thomas Henwood (Fig. 1.17) captured the event. Snow avalanches are a form of mass movement (Griffiths 2018) and, while the failure mechanisms are similar to those encountered in landslides, the techniques of investigation and mitigation are quite different and lie more in the field of snow science than engineering geology.

Another subject that crosses the boundary between geohazards, hydrogeology and meteorological hazards is flooding, whether inland from rivers or on the coast. Flooding by rivers is a natural geomorphological process, although the consequences may be exacerbated by humans who build structures in unsuitable locations, strip vegetation that would have

Fig. 1.17. The avalanche at Lewes, 1836, attributed to Thomas Henwood (Anne of Cleves House, East Sussex).

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Fig. 1.18. Thames Barrier, London (photo credit: Andy Roberts).

reduced runoff, and cover areas with impermeable tarmac that increases the peak flow. On the coast, flooding by the sea is related to sea-level height, tides and waves. Coastal flooding as a result of tsunamis generated by earthquakes or submarine landslides is a phenomenon the UK does need to take into account, and this is discussed in Chapter 3 (Giles 2020*b*). Physical barriers to flooding are structures that require input by engineering geologists; these may be simple earthworks bunds alongside rivers or major concrete sea defences. The 1953 coastal floods in East Anglia that killed more than 300 people, caused by a storm surge in the North Sea (Orford 2005), resulted in the widespread construction of better sea defences. The most prominent of these was the Thames Barrier at Greenwich that was completed in 1984 and was designed to protect London from a similar event (Fig. 1.18); rising sea levels associated with global climate change suggest it is reaching the end of its design life. Because such events are driven by meteorological events, it was decided not to include a discussion on flooding in the Working Party Report, although it is accepted that this is a contestable viewpoint.

As demonstrated by the above discussion, deciding on what geohazards to include in any evaluation of the situation in the UK is not straightforward or without controversy. However, boundaries had to be established and, as a consequence, some topics were omitted that would have been very relevant in other countries (e.g. volcanicity in Italy). The overall aim, however, was to provide an evaluation of those geohazards that engineering geologists were most likely to encounter and have to mitigate against in UK practice.

1.4 Section A: tectonic hazards

1.4.1 Chapter 2: seismic hazard in the UK (Musson 2020)

A popular misconception among the wider public is that earthquakes do not occur in the UK; however, the UK is classified as having a low-to-moderate seismic risk with, on average, a magnitude 3.2 M_w (moment magnitude) or larger earthquake occurring once per year, and a magnitude 4.2 M_w or larger every 10 years. The latter is capable of causing non-structural damage to property. The damage caused by British earthquakes is generally not life threatening, and no one has been killed in a British earthquake (at the time of publication) since 1940. Damage is caused by shaking, not by ground rupture. Seismic hazard can be discounted for most ordinary construction in the UK, but this is not the case for high-consequence facilities such as dams, bridges and all power plants but especially nuclear power plants, where very long timescales have to be considered as a consequence of the long half-life of radioactive materials.

The diffuse spread of earthquakes across the UK means that there are hundreds of faults in the country that have been reactivated and produced (albeit minor) earthquakes. In almost all cases, however, a known, named fault cannot be shown to have been the origin of a specific earthquake. Small earthquakes have small source dimensions and require only a small fault; these are numerous, and the location of an earthquake in three dimensions is not precise beyond a few kilometres at best. There may be several potential fault sources, or the real fault source may be unmapped. In the UK, the spatial distribution of earthquakes is not uniform or random (Fig. 1.19). In Scotland, most earthquakes are concentrated on the west coast with the addition of centres of activity near the Great Glen at Inverness (earthquakes in 1816, 1890 and 1901) and a small area around Comrie, Perthshire, the site of the famous earthquake swarms principally in 1795–1801 and 1839–1846, and possibly also 1605–1622. Since 1846 small shocks have been observed at Comrie on a regular, if infrequent, basis. There has also been swarm activity in the Central Valley of Scotland by the Ochil Hills (near Stirling). This spot was active in 1736, during 1900–1916 and in 1979.

The Outer Hebrides, off the west coast of Scotland, the extreme north (including the islands of Orkney and Shetland) and most of the east of Scotland are virtually devoid of earthquakes. However, for the northwestern reaches of Scotland the absence of early written records, the small population and the recent lack of recording instruments means that there may be a data gap.

Further south in England and Wales, a similar irregularity is seen. Wales and the west of England, including the SW and NW parts of the country and the English Midlands, are much more active than the east of England. NE England seems to be very quiet; the SE has a higher rate of activity with a number of earthquakes that seem to be ‘one-off’ occurrences, plus a couple of important centres of activity on the south coast. It is curious that the damaging 1884 Colchester earthquake occurred in a locality of SE England that seems to have been otherwise very inactive seismically, either before or since.

Offshore, there is significant activity in the English Channel and in the North Sea off the coast of Humberside. Because only the larger events in these places are likely to be felt

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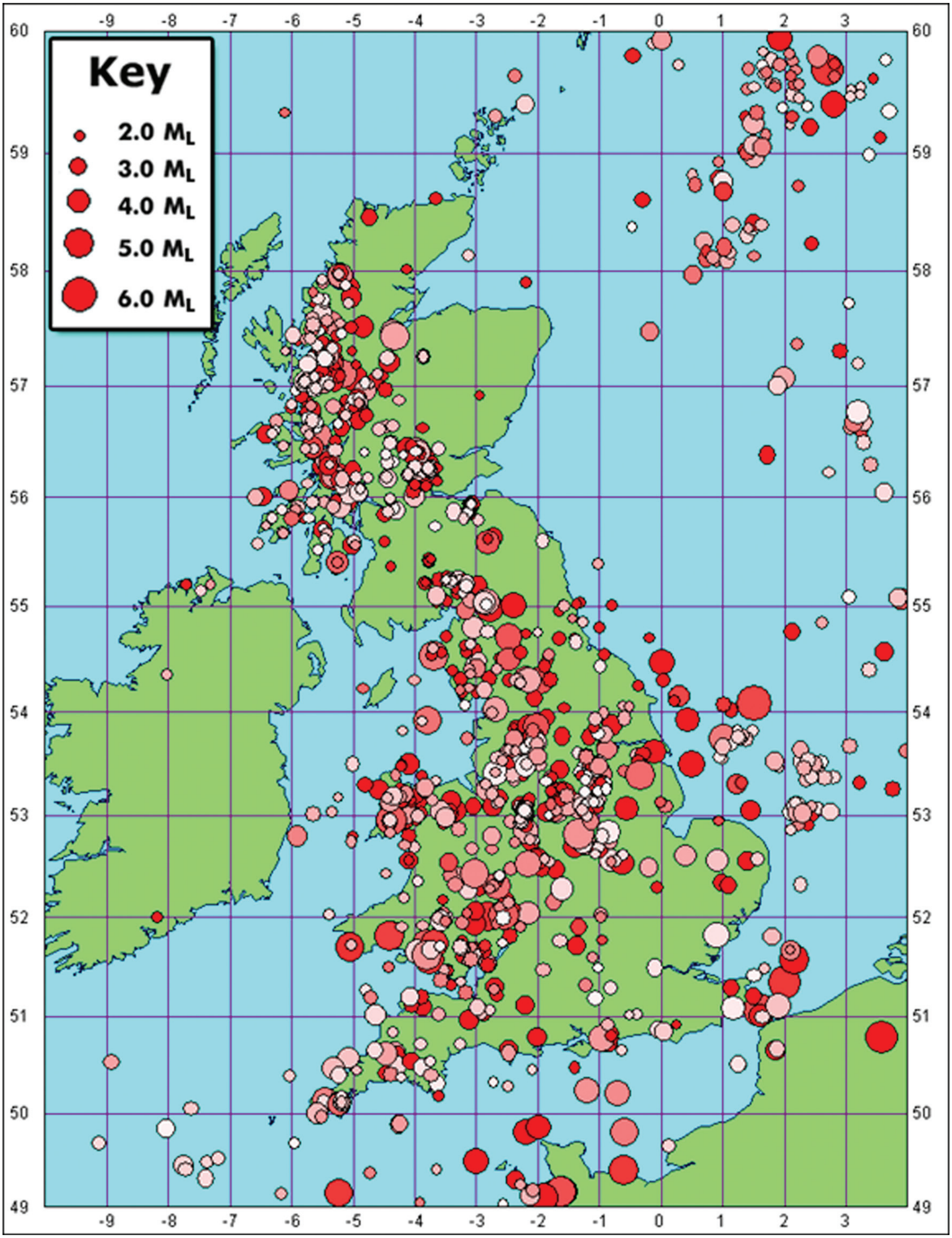

Fig. 1.19. Seismicity of the UK. Depths are indicated by colour: paler shades imply shallower; unknown depths in bright red (Musson 2020).

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onshore, the catalogue is probably under-representative of the true rate of earthquake activity in these zones. The largest British earthquake for which magnitude can be estimated had an epicentre in the North Sea, off the east coast of England. This occurred on 7 June 1931 with an estimated magnitude of 5.8 M_w (moment magnitude), and the earthquake was felt over the whole of Great Britain, eastern Ireland and in all the countries bordering the North Sea. It is fortunate that this earthquake had an offshore epicentre as the damage might have been considerable otherwise; only minor damage occurred up the east coast.

Certain centres can be identified as showing typical patterns of activity. For example, the NW corner of Wales is one of the most seismically active places in the whole UK. Both large and small earthquakes, usually accompanied by many aftershocks, occur at regular intervals. In South Wales, on the other hand, although a line of major epicentres can be traced from Pembroke to Newport, only the Swansea area shows consistent recurrence. The Hereford–Shropshire area of western England adjoins South Wales, and this area has also experienced large earthquakes in 1863, 1896, 1926 and 1990; these have no common epicentre, however. In the north of England seismic activity occurs principally along the line of the Pennine Hills, which form the backbone of this part of the country. Again, it is possible to identify particular spots that have been active repeatedly.

The area of the Dover Straits is particularly significant because of the occurrence there of two of the largest British earthquakes in 1382 and 1580 (both of magnitude about 5.5 M_w). Jersey has also experienced a number of significant earthquakes, chiefly originating to the east of the island in the Cotentin peninsula area of France.

What is remarkable is the lack of correlation between this pattern and the structural geology of the UK. In the northern part of the British Isles, the geology has a strong NE–SW (Caledonian) trend and the geology of Northern Ireland is largely a SW-wards extension of the geology of Scotland. However, there is no continuity of seismicity along this trend. It is possible to draw a line roughly NNW–SSE through Scotland such that earthquakes are entirely confined to the west side of the line; yet this line has no apparent geological significance and cuts directly across the structural trend. It is clear that this pattern is persistent and not merely an artefact of recent earthquake locations; there are a number of historical sources for the east of Scotland which comment on the absence of earthquakes. The difficulty is acute in Ireland; the geological history of Ireland is very similar to that of Great Britain, and there is no clear solution to the question of why the seismicity of Ireland should be so very much lower. Scottish seismicity coincides with those areas under ice in the last phase of the last glaciation. In Scotland, stresses due to isostatic recovery after the last glaciations, with a sort of ‘jostling’ of different geological units in response to an overall compressive stress, were exerted from the NW in response to Atlantic widening.

The frequency of earthquakes in any region is known to be inversely related to the magnitude of the shock, according to what is known as the Gutenberg–Richter equation. Figure 1.20 shows the application of this to the UK, using data from 1970 to 2007. The relationship represented by the red line is:

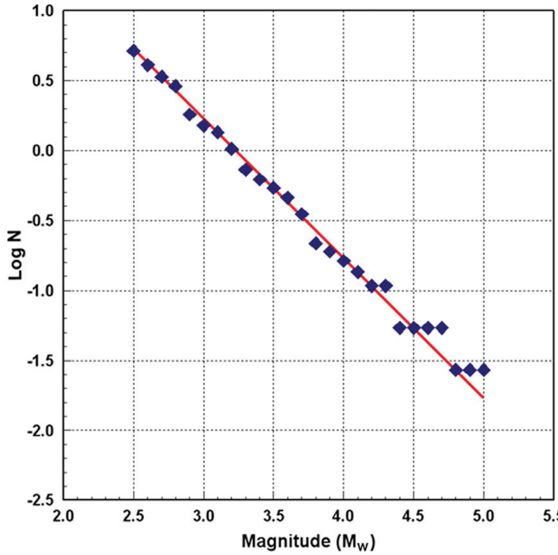

Fig. 1.20. Gutenberg–Richter relationship for UK seismicity (Musson 2020).

$$\log N = 3.23 - 1.00\,M_w \qquad (1)$$

where N is the number of earthquakes per year equal to or larger than a given M_w magnitude. The value of −1.0 coincides with the expected value from theory and practice, and generally equates to that over northern Europe.

1.4.2 Chapter 3: tsunami hazard with reference to the UK (Giles 2020*b*)

Tsunami present a significant geohazard to coastal and water-body marginal communities worldwide. Tsunami, a Japanese word, describes a series of waves that travel across open water with exceptionally long wavelengths (up to several hundred metres in deep water) and with very high velocities (up to 950 km hr^{-1}) before shortening and slowing on arrival at a coastal zone. On reaching land, these waves can have a devastating effect on the people and infrastructure in those environments. Until relatively recently, the understanding of tsunami events and their historic catalogue had been quite poor. The 2004 Indian Ocean Boxing Day tsunami and the 2011 Tohoku event in Japan tragically brought this geohazard to the attention of the wider population and instigated a deeper investigation and research into these geological phenomena.

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Tsunamis can be generated through a variety of mechanisms, including the sudden displacement of the sea floor in a seismic event as well as submarine and onshore landslides displacing a mass of water. Typically, tsunami are generated by tsunamigenic earthquakes, tsunamigenic landslides, tsunamigenic volcanism and meteotsunami.

With its 12 429 km of coastline, the UK is no less prone to the impact of tsunami as the Indian or Pacific oceans. In 2005, Defra commissioned a study precipitated by the Indian Ocean disaster to consider the potential impact on the UK from such events. This review presents those impacts together with a summary of tsunami triggers and UK case histories from the known historic catalogue. Seven potential source zones that could affect the UK (Fig. 1.21) were categorized in terms of their probability of occurrence, namely: UK coastal waters; NW European continental slope; plate boundary west of Gibraltar; Canary Islands; Mid-Atlantic Ridge; eastern North American continental slope; and the Caribbean.

Some notable tsunami events with a UK impact include the *c.* 8150 BP Holocene Storegga submarine landslide and tsunami, the *c.* 5500 BP Holocene Garth tsunami, the tsunami generated by the 1755 Lisbon earthquake, and a local

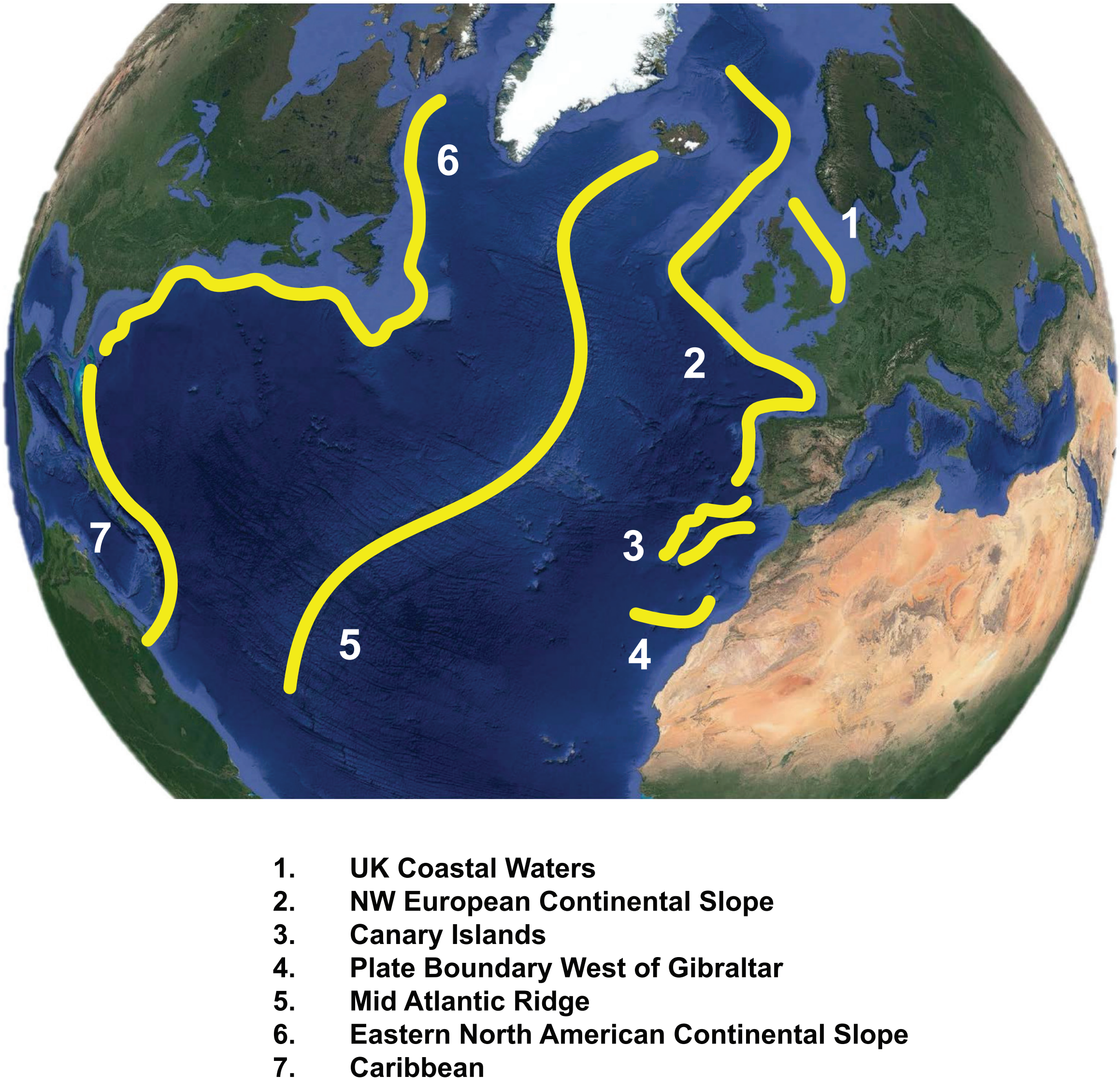

Fig. 1.21. Possible tsunami source zones with a potential UK impact as considered by Defra (Giles 2020*b*).

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event generated by the 1911 Abbots' Cliff failure at Folkestone, Kent.

1.5 Section B: slope stability hazards

1.5.1 Chapter 4: landslide and slope stability hazard in the UK (Lee & Giles 2020)

For many people above a certain age the word 'landslide' will evoke memories of the Aberfan disaster of 21 October 1966. A rotational failure at the front of a colliery spoil tip on the flanks of a steep-sided South Wales valley transformed into a flow slide which travelled downslope at around 10 m s^{-1} into the village. The debris ran out 605 m, building up behind the rear wall of the Pantglas Primary School, causing it to collapse inwards. The loose waste then filled up classrooms, killing 116 children and 28 teachers. The community was severely affected, with many suffering severe psychological difficulties after the disaster. However, Aberfan presents a misleading picture about the nature of landsliding in the UK. The deaths caused by this single event almost certainly exceeded the overall loss of life from all other landslide events in the UK over the last few centuries. Fatal accidents in the UK are extremely rare and tend to be the result of rockfalls or high-velocity slides on the coast, rather than in inland valleys (Fig. 1.22). For example, in July 2012 a young woman was killed by a large rockfall on the beach at Burton Bradstock, Dorset. In February 1977 a school party were studying the geology of Lulworth Cove, Dorset, when they were buried beneath a rockslide; the schoolteacher and a pupil were killed and two more pupils seriously injured, one of whom died later in hospital. In July 1979 a woman sunbathing on the beach near Durdle Door, Dorset, was killed when a 3 m overhang collapsed.

Although the incidents on the Dorset coast during the 1970s led the then Chief Inspector of Wareham police to coin the phrase 'killer cliffs', the public perception of coastal erosion is dominated by the fear that parts of the UK are being rapidly lost to the sea, raising visions of a loss of national resources to a hostile invading power (Table 1.2).

The most intense marine erosion and cliff recession rates occur on the unprotected cliffs formed of soft sedimentary rocks and glacial deposits along the south and east coasts of England, respectively. The Holderness coast, for example, has retreated by around 2 km over the last 1000 years, including at least 26 villages listed in the Doomsday survey of 1086; 75 Mm^3 of land has been eroded in the last 100 years. Rapid recession has also caused severe problems on the Suffolk coast, most famously at Dunwich where much of the former town has been lost over the last millennium. Gardner (1754) recorded that, by 1328, the port was virtually useless and 400 houses together with windmills, churches, shops and many other buildings were lost in one night in 1347. On parts of the north Norfolk coast there has been over 175 m of recession since 1885; county archives show that 21 coastal towns and villages have been lost since the eleventh century. Today, the reality of coastal erosion is often very different, primarily because of the effectiveness of over 850 km of coastal protection measures built mainly over the last 130 years. The average annual loss of land due to cliff recession and coastal landsliding around the coast of England is probably less than 10–25 ha.

High-velocity landslide events that present a threat to people do occur inland, such as the August 2004 debris flows in the Scottish Highlands (see Chapter 5; Winter 2019). There were no fatalities, but 57 people had to be airlifted to safety by the RAF when they became trapped between debris flows on the A85 at Glen Ogle. Two people were killed in July 2012 when their car was crushed by falling debris as it emerged from the Beaminster Tunnel, Dorset, due to a landslide bringing down part of the tunnel portal. However, most inland landslides generally present only minor threats to life as movements, when they occur, usually involve only slow and minor displacements. Even when large displacements occur, the rate of movement tends to be gentle and not dramatic, as was reported graphically for the French House slide near Lympne, Kent, in 1725 where a farmhouse sank 10–15 m overnight, 'so gently that the farmer's family were ignorant of it in the morning when they rose, and only discovered it by the door-eaves, which were so jammed as not to admit the door to open' (Gostling 1756).

Nevertheless, slow-moving inland landslides can have a significant economic impact. The cumulative effects of episodes of slow movement can inflict considerable damage to buildings, services and infrastructure. Almost continuous damage from movement of the Mam Tor landslide in the High Peak of Derbyshire led to the permanent closure of the A625 Manchester–Sheffield road in 1979 and diversion of local and cross-Pennine traffic. Hutchinson (2001) describes how a power line from Dungeness Nuclear Power Station, Kent, was put out of action for over a month in the winter of 1966/67 when landslide activity on the Hythe–Lympne escarpment led to the loss of a pylon. Sustained rainfall in November 1998 led to the collapse of Greenan Road near Ballycastle, Northern Ireland, cutting off access to a farming community; as the farms quickly ran out of feed for their livestock, helicopters were used to bring in fresh supplies. There has been a history of mudslides blocking the Antrim coast road, particularly at Minnis North. For example, in a 14-month period between 1971 and 1972 there were 10 incidents when the road was blocked. Intense rainfall on the morning of Tuesday 8 November 2005 initiated a small peat slide on a hillside above the A5 London–Holyhead trunk road in the Llyn Ogwen area, Snowdonia National Park; four people were injured, a nearby construction project was delayed and A5 was blocked. In February 2013, a landslide occurred in a spoil tip at Hatfield Main Colliery and severely damaged a large section of train line along the Doncaster–Goole and Doncaster–Scunthorpe lines. The section of the line was closed for 5 months and train services in the region significantly affected.

The unforeseen presence of ancient landslides can lead to costly problems during construction. The A21 Sevenoaks

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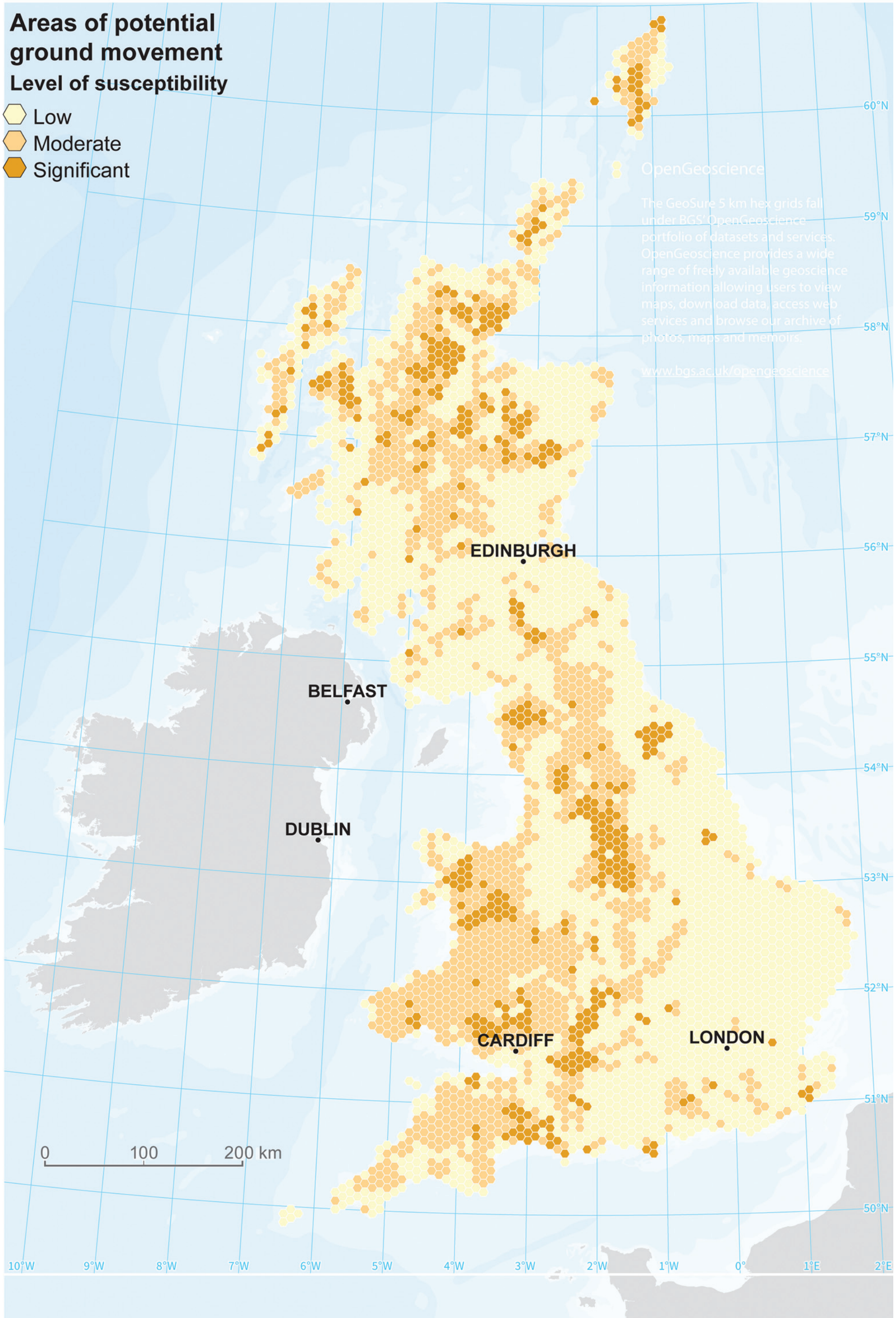

Fig. 1.22. Landslide susceptibility map of the UK (Lee & Giles 2020).

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Table 1.2. *Significant landslide fatalities in the UK (British Geological Survey National Landslide Database)*

Landslide Event	*Year*	*Fatalities*	*Mechanism (after Varnes 1978)*	*Land system*
Bwlch Y Saethau pass, Snowdon, Gwenydd	2018	1*	Rock fall	Coastal
Cwmdaud, Carmarthenshire	2018	1*	Slide	River valley
Staithes, Yorkshire	2018	1	Rock fall	Coastal
Thorpeness, Suffolk	2017	1	Rock fall	Coastal
Llantwit Major, Vale of Glamorgan	2015	1	Rock fall	Coastal
Sandplace Road, Looe, Cornwall	2013	1	Slide	Coastal
Burton Bradstock, Dorset	2012	1	Rock fall	Coastal
Beaminster Tunnel, Dorset	2012	2	Slide	Hillside
Newbiggin, Northumberland	2010	1	Rock fall	Coastal
Whitehaven, Cumbria	2007	1	Debris fall	Coastal
Ben Nevis, Lochaber	2006	1	Rock fall	Upland
Nefyn, Gwynedd	2001	1	Debris flow	Coastal
Marine Drive, Gogarth, Gwynedd	1987	1	Rock fall	Coastal
Newquay, Cornwall	1986	1	Rock fall	Coastal
Durdle Door, Dorset	1979	1	Rock fall	Coastal
Lulworth Cove, Dorset	1977	3	Rock fall	Coastal
Swanage Bay, Dorset	1976	1	Rock fall	Coastal
Kimmeridge Bay, Dorset	1971	1	Rock fall	Coastal
Aberfan, South Wales	1966	144	Debris flow	Anthropogenic
Alum Bay, Isle of Wight	1959	1	Rock fall	Coastal
Boscombe, Dorset	1925	3	Rock fall	Coastal
Loch Ness, Scotland	1877	1	Rock fall	Upland
Early's Wall, Dawlish	1855	3	Rock fall	Coastal
Sonning Cutting, Reading, Berkshire	1841	9	Slide/flow	Anthropogenic
Guildford Battery, East Cliff, Dover	1810	7	Rock fall	Coastal
Pitlands Slip, Isle of Wight	1799	2	Rock fall	Coastal

*Landslides not yet confirmed; inquest currently underway.

Bypass, Kent, had to be halted in 1966 when excavation work cut through grass-covered lobes of material that proved to be the remains of a previously unidentified ancient landslide. The inadvertent removal of material from the lower portion of these landslides led to their reactivation, despite the fact that they appeared to have remained stable and stationary over the Holocene. The problems turned out to be so severe that the affected portion of the route had to be realigned. This incident and a similar landslide problem on the M6 motorway embankment at Waltons Wood provided the impetus for UK-based academic research into inland landslides.

In many instances landslide problems are less newsworthy, although they can still lead to property loss or the delay, redesign or abandonment of projects. For example, Camden Crescent in Bath is the only known asymmetric crescent in the world; half had been destroyed by the Hedgemead landslide in 1894. In 1952, a landslide occurred at the village of Jackfield, Shropshire, on the River Severn just over 2 km downstream of the Iron Bridge, destroying several houses and causing major dislocations in a railway and road. Instability problems encountered at housing developments at Bury Hill and Brierley Hill in the West Midlands, at Exwick Farm on the outskirts of Exeter, at Ewood Bridge in the Irwell Valley and at Gypsy Hill in South London are some examples of the impact of localized slope instability frequently associated with smaller-scale developments. A large landslide in 1993 at Franklands Village, West Sussex, led to the demolition of 14 flats and houses.

This chapter considers all aspects of landslide and slope stability from outlining the hazard, assessing the risk and managing the risk posed by problematic slopes.

1.5.2 Chapter 5: debris flows (Winter 2020)

Debris flows are largely fast moving and dynamic in nature; they are generally characterized by rapid movement with high proportions of either water or air acting as a lubricant for the solid material that generally comprises the bulk of their mass. Given the right circumstances, they can be highly destructive. In the UK their presence is largely, although not exclusively, restricted to mountainous areas. Indeed, the UK landslides research community has historically focused on slow-moving events that, in general, lead to economic losses such as those at Ventnor on the Isle of Wight and Folkestone Warren.

The fast-moving debris-flow events in Scotland in August 2004 and since provide a rich source of case study material; it was fortuitous that there were no major injuries to those involved in those events. However, even in the absence of serious injuries and fatalities, the socioeconomic impacts of such events may be serious. These include the severance

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(or delay) of access to and from relatively remote communities for: markets for goods and services; employment, health and educational opportunities; and social activities. The extent of these impacts is described by the vulnerability shadow. The work that has followed has therefore drawn on the more traditional approach to slow-moving landslides, as well as that typified by the international approach to fast-moving events that pose a real risk to life and limb.

Hillslope (or open-slope) debris flows form their own path down valley slopes as tracks or sheets, before depositing material on lower areas with lower slope gradients or where flow rates are reduced (e.g. obstructions, changes in topography; Fig. 1.23). The deposition area may contain channels and levees. The motion of such events is generally considered not to be maintained when the width exceeds five times the average depth. As the mobilized material in such events rarely persist to either the level of the slope at which transport infrastructure exists, or to the valley floor in Scotland, they are therefore of relatively little practical interest.

Channelized debris flows follow existing channel-type features, such as valleys, gullies and depressions, are often of high density, comprise 80% solids by weight, and may have a consistency equivalent to that of wet concrete; they can therefore transport boulders that are some metres in diameter.

In this chapter, the work undertaken for a hazard and risk assessment for debris flow affecting the Scottish road network is briefly referred to in terms of: a GIS-based assessment of debris-flow susceptibility; a desk-/computer-based interpretation of the susceptibility and field-based ground-truthing to determine hazard; and a desk-based exposure analysis to enable the determination of risk.

A strategic approach to landslide risk reduction allows a clear focus on that overall goal before homing in on the desired outcomes and the generic approach to achieving those outcomes. Only then are the processes that may be used to achieve those outcomes (i.e. the specific management and mitigation measures and remedial options) addressed. A top-down, rather than a bottom-up, approach is therefore targeted. Risk reduction is considered as: relatively low-cost exposure reduction (management) outcomes that allow specific measures to be extensively applied; and relatively high-cost hazard reduction (mitigation) outcomes that include measures that are targeted at specific sites.

In addition to covering the above themes, this chapter also considers the potential effects of future climate change on debris-flow hazard and risk, again using Scotland as an example.

1.6 Section C: problematic ground and geotechnical hazards

1.6.1 Chapter 6: collapsible soils in the UK (Culshaw *et al.* 2020)

Metastable soils may collapse because of the nature of their fabric. These soils have porous textures, high void ratios and low densities. They have high apparent strengths at their natural moisture content but large reductions of void ratio take place on wetting and, particularly, when on loading, because bonds between grains break down on saturation. Worldwide, there is a range of natural soils that are metastable and can collapse including: loess; residual soils derived from the weathering of acid igneous rocks and from volcanic ashes and lavas; rapidly deposited and then desiccated debris-flow materials such as some alluvial fans (e.g. in semi-arid basins); colluvium from some semi-arid areas; and cemented, high-salt-content soils such as some sabkhas. In addition,

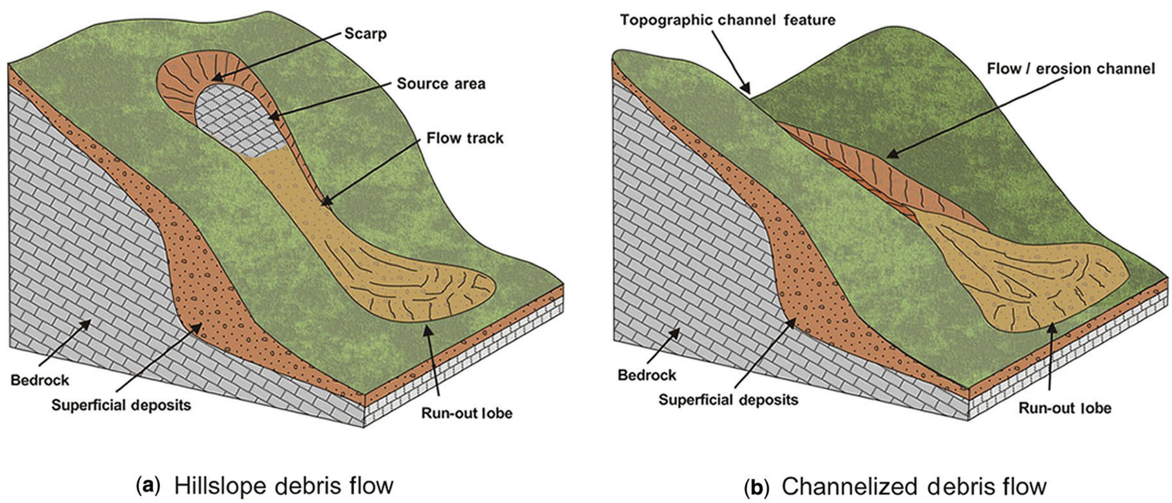

Fig. 1.23. (**a**) Hillslope and (**b**) channelized debris flow (Winter 2020).

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some artificial non-engineered fills can also collapse. The main type of collapsible soil in the UK is loess, although collapsible non-engineered fills also exist. Loess in the UK can be identified from geological maps, but care is needed because it is usually mapped as 'brickearth'. This is an inappropriate term and it is suggested here that it should be replaced with the term 'loessic brickearth'. Loessic brickearth in the UK is found mainly in the SE, south and SW of England, where thicknesses greater than 1 m are found. In Great Britain, loessic deposits are mapped by the British Geological Survey mainly as 'brickearth'. Such deposits occur mainly as a discontinuous spread across southern and eastern England, notably in Essex, Kent, Sussex and Hampshire (Fig. 1.24).

Elsewhere, thicknesses are usually less than 1 m and, consequently, of limited engineering significance. There are four steps in dealing with the potential risks to engineering posed by collapsible soils: (1) identification of the presence of a potentially collapsible soil using geological and geomorphological information; (2) classification of the degree of collapsibility, including the use of indirect correlations; (3) quantification of the degree of collapsibility using laboratory and/or in situ testing; and (4) improvement of the collapsible soil using a number of engineering options.

Fig. 1.24. Surface distribution of loess/brickearth in south UK based on Soil Survey 1:250 000 scale soil maps (1983). Loess >1 m thick in black; loess >300 mm thick (and often partly mixed with subjacent deposits) shown stippled (Culshaw *et al.* 2020).

Soils that have the potential to collapse generally possess porous textures with high void ratios and relatively low densities. At their natural moisture content, these soils possess high apparent strength but are susceptible to large reductions in void ratio on wetting, especially under load. In other words, the metastable texture collapses as the bonds between the grains break down as the soil becomes saturated. As collapse is controlled both microscopically and macroscopically, both these elements need to be understood if the true nature of collapse is to be determined. The potential for soils to collapse is clearly of geotechnical significance, particularly with respect to the potential distress of foundations and services (e.g. pipelines) if not recognized and designed for. The collapse process represents a rearrangement of soil particles into a denser state of packing. Collapse on saturation usually occurs rapidly. As such, the soil passes from an underconsolidated condition to one of normal consolidation. There are two basic requirements for a soil to be collapsible: a collapsible soil is one in which the constituent parts have an open packing and which forms a metastable state that can collapse to form a closer packed, more stable structure of significantly reduced volume'; and 'in most collapsible soils the structural units will be primary, mineral particles rather than clay minerals.

The most widespread naturally collapsible soils are loess or loessic soils of aeolian origin, predominantly of silt size with uniform sorting. The majority of these soils have glacial associations in that it is believed that these silty soils were derived from continental areas where silty source material was produced by glacial action prior to aeolian transportation and deposition. There are four fundamental requirements necessary for the formation of loess: a dust source; adequate wind energy to transport the dust; a suitable depositional area or reduced wind speed; and sufficient time for its accumulation and epigenetic evolution.

These requirements are not specific to any one climatic or vegetational environment. While much loess was formed in glacial/periglacial environments, derived from the floodplains of glacial braided rivers where glacially ground silts and clays were deposited, windblown deposits can be derived in other environments, such as volcanic, tropical, desert and gypsum loesses; climatically controlled windblown deposits are referred to as trade-wind and anticyclonic.

Collapsible soils, including loess, are materials that standard soil mechanics stress–strain principles fail to adequately explain in terms of their engineering behaviour. For the ground engineering industry to avoid and mitigate the risks associated with collapse, a first significant step is to correctly identify the presence of collapsible soils. Once identified, appropriate laboratory testing procedures and, where necessary, follow-up field tests can be applied to assess collapse potential and the possible need for mitigation measures. This chapter describes the current geological, geotechnical, geochemical, mineralogical and geomorphological understanding of UK collapsible soils and may serve as a guide to aid engineering ground investigation in those areas where such natural (loessic) soils and potentially collapsible

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anthropogenic fills may be present. Current techniques to help mitigate the risks associated with collapse are also described. As planned expansion of the UK road and rail infrastructure progresses, it becomes ever more important that the collapse potential of poorly or non-engineered fills, including old Victorian railway embankments, is considered by ground engineers, and that the use and appropriate engineered placement of potentially metastable materials is more fully understood and designed for.

1.6.2 Chapter 7: quick-clay behaviour in sensitive Quaternary marine clays: UK perspective (Giles 2020*a*)

The term 'quick clay' has been used to denote the behaviour of highly sensitive Quaternary marine clays that, due to post depositional processes, have the tendency to change from a relatively stiff condition to a liquid mass when disturbed. On failure, these marine clays can rapidly mobilize into high-velocity flow slides and spreads, often completely liquefying in the process. For a clay to be defined as potentially behaving as a quick clay in terms of its geotechnical parameters, it must have a sensitivity (the ratio of undisturbed to remoulded shear strength) of greater than 30, together with a remoulded shear strength of less than 0.5 kPa. Potential quick-clay-behaving soils can be found in areas of former marine boundaries that have been uplifted through isostatic rebound after Quaternary glaciations. The presence of quick clays in the UK is unclear, but the Quaternary history of the British islands suggests that the precursor conditions for their formation could be present and should be considered when undertaking construction in the coastal zone.

Deposits prone to quick-clay behaviour develop from initially marine clays deposited from rock-flour-rich meltwater streams feeding into a nearshore marine environment (Fig. 1.25). On glacial retreat, crustal rebound (isostatic recovery) uplifts the marine sediments above current sea level, eventually exposing them to a temperate weathering environment and soil leaching by freshwater. In Norway, for example, the former syn-glacial sea level can be found up to 220 m higher than present-day sea levels.

For clay to develop 'quick' properties, the sediment must have a flocculated structure and a high void ratio. This flocculated structure would be the normal state in which fine-grained sediments formed from glacial erosion had been deposited in marine and brackish subaqueous environments. In this setting, silt- and clay-sized particles would rapidly flocculate to form these high-void ratio sediments. Generally, in freshwater sedimentary environments clay-sized particles

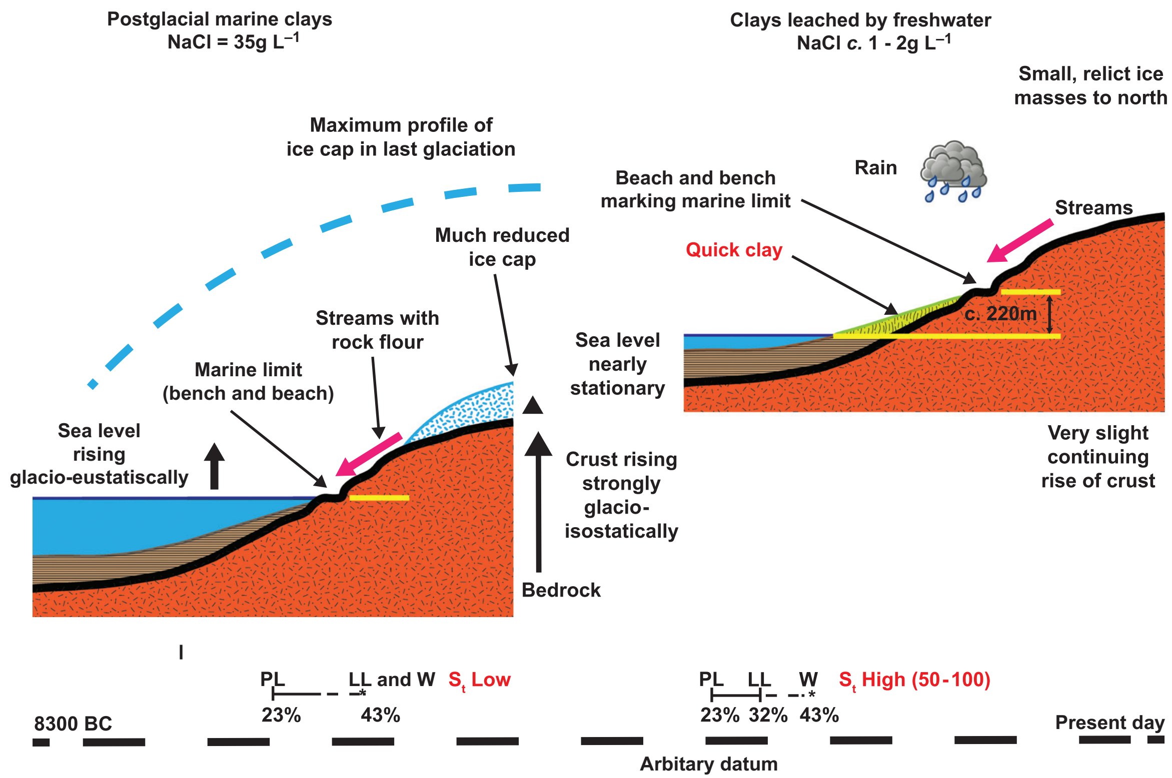

Fig. 1.25. The development of quick clays through the Holocene (Giles 2020*a*). PL, plastic limit; LL, liquid limit; W, natural moisture content; S_t sensitivity.

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settle even more slowly than silt grains, and tend to accumulate in a dispersed structure with a parallel orientation of particles. In more saline conditions, silt and clay particles form aggregates (small flocculates) and settle together in a random pattern. This random alignment of particles (in effect a 'house of cards' structure) gives the flocculated material a higher-than-normal void space and hence potentially higher moisture content. Quick-clay sediments originally deposited in marine or brackish conditions initially had a porewater geochemistry of up to 35 g L^{-1} sodium chloride. Subsequent uplift of the strata to above sea level resulted in them being subject to temperate weathering conditions where soil leaching by freshwater occurred. This weathering created a top crust of leached material with a subsequent reduction in the strength of the former marine clays. The sodium chloride porewaters were progressively leached by rainwater and freshwater streams, reducing the salt content to around 1–2 g L^{-1}. This had the effect of generating very sensitive clay-dominated soils that exist in a metastable state. Potential quick-clay-behaving sediments can be identified by their geotechnical properties, in particular by their sensitivity, the ratio of undrained shear strength to remoulded shear strength at the same moisture content, and by their activity.

Various studies on postglacial isostatic recovery and eustatic sea-level adjustment indicate that parts of the UK coastal zone have been elevated above former sea levels. The possibility that former fine-grained marine sediments have subsequently been elevated above sea level and have been subject to weathering processes and potential porewater leaching potentially exists in these now-onshore coastal areas. The uplifted zones will have experienced the pre-conditions for quick-clay-behaving sediments to be developed. In terms of ground investigation in these areas, the geotechnical properties of any fine-grained sediments encountered need to be considered with respect to potential quick-clay behaviour, specifically with respect to the sensitivity and activity of the deposit as well as the nature of the mineral content of the soil. An awareness that these soils could be prone to rapid failure, coupled with a complete remoulding of the soil with the associated liquefaction, needs to be taken into account in the design and implementation of construction works and must form part of the hazard assessment and project risk management.

1.6.3 Chapter 8: swelling and shrinking soils (Jones 2020)

Shrink–swell soils are one of the most costly and widespread geological hazards globally, with costs estimated to run into several billion pounds annually. These soils present significant geotechnical and structural challenges to anyone wishing to build on, or in, them. Shrink–swell occurs as a result of changes in the moisture content of clay-rich soils, reflected in a change in volume of the ground through shrinking or swelling. Swelling pressures can cause heave or lifting of structures while shrinkage can cause differential settlement. This chapter aims to give the reader a basic understanding of shrink–swell soils. A review is provided on the nature and extent of shrink–swell soils, both in the UK and worldwide, discussing how they form, how they can be recognized, the mechanisms and behaviour of shrink–swell soils, and the strategies for their management (including avoidance, prevention and mitigation).

A shrink–swell soil is one that changes in volume, in response to changes in its moisture content. The extent of the volumetric change reflects the type and proportion of swelling clay in the soil. More specifically, expansive clay minerals expand by absorbing water and contract, or shrink, as they release water and dry out. Clays range in their potential to absorb water according to their different structures. For the most expansive clays, expansions of 10% are common.

In practice, the amount by which the ground shrinks and/or swells is determined by the water content in the near-surface (active) zone. Soil moisture in this zone responds to changes in the availability of atmospheric recharge and the effects of evapotranspiration. These effects usually extend to about 3 m depth, but this may be increased by the presence of tree roots. Characteristically fine-grained clay-rich soils soften, becoming sticky and heavy following recharge events such as rainfall, and commonly can absorb significant volumes of water. Conversely, as they dry, shrinking and cracking of the ground is associated with a hardening of the clay at surface. Structural changes in the soil during shrinkage, for example, alignment of clay particles, ensure that swelling and shrinkage are not fully reversible processes. For example, the cracks that form during soil shrinkage are not perfectly annealed on re-wetting. This volume increase results in a decrease in the soil density, thereby providing enhanced access by water for subsequent episodes of swelling. In geological timescales, shrinkage cracks may become infilled with sediment, thus imparting heterogeneity to the soil. Once the cracks have been infilled in this way, the soil is unable to move back, leaving a zone with a network of higher permeability infills. When supporting structures, the effects of significant changes in water content on soils with a high shrink–swell potential can be severe. In practical civil engineering applications in the UK, there are three important time-dependent situations, each with different boundary conditions, where shrink–swell processes need to be considered: (1) following a reduction in mean total stress (the most notable effects are found adjacent to cut slopes, excavations and tunnels); (2) subsurface groundwater abstraction or artificial/natural recharge under conditions of constant total stress in both unconfined and confined aquifers (regional subsidence or heave can be induced by this process); and (3) surface climatic/water balance fluctuations related to land-use change under conditions of constant total stress (the most notable effects follow the development of seasonally desiccated soils, which can cause structural damage to existing shallow foundations).

As well as effective stress changes, some deformation may be caused by biogeochemical alteration and dissolution of minerals as a result of steady-state fluid transport processes. Although surface movements and engineering problems

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can occur due to a loss or addition of solid material, these are not strictly shrink–swell soils. However, these processes are often combined with effective stress changes and/or fluid movements, and may therefore be difficult to separate from true shrink–swell processes that might be taking place at the same time. The main factors controlling shrink–swell susceptibility in geological formations are material composition (clay mineralogy), initial *in situ* effective stress state and stiffness of the material. Variations in the initial condition caused through processes such as original geological environment, climate, topography, land-use and weathering affect *in situ* effective stress, stiffness and hence shrink–swell susceptibility. Clays belonging to the silicate family comprise the major elements silicone, aluminium and oxygen. There are many other elements that can become incorporated into the clay mineral structure (hydrogen, sodium, calcium, magnesium and sulphur). The presence and abundance of these dissolved ions can have a large impact on the behaviour of the clay minerals. The clay minerals are defined by the ratio of silica tetrahedra to alumina, iron or magnesium octahedra.

Subsidence also occurs in superficial deposits such as alluvium, peat and laminated clays that are susceptible to consolidation settlement (e.g. in the Vale of York, east of Leeds, and in the Cheshire Basin), but these are not true shrink–swell soils.

1.6.4 Chapter 9: peat hazards: compression and failure (Warburton 2020)

Peat is a low-density, highly compressible soil that occurs at the surface or may be buried at depth. Peat is essentially an organic, non-mineral soil resulting from the decay of organic matter. In the UK, peat deposits are widespread occurring in a wide variety of upland and lowland environments covering

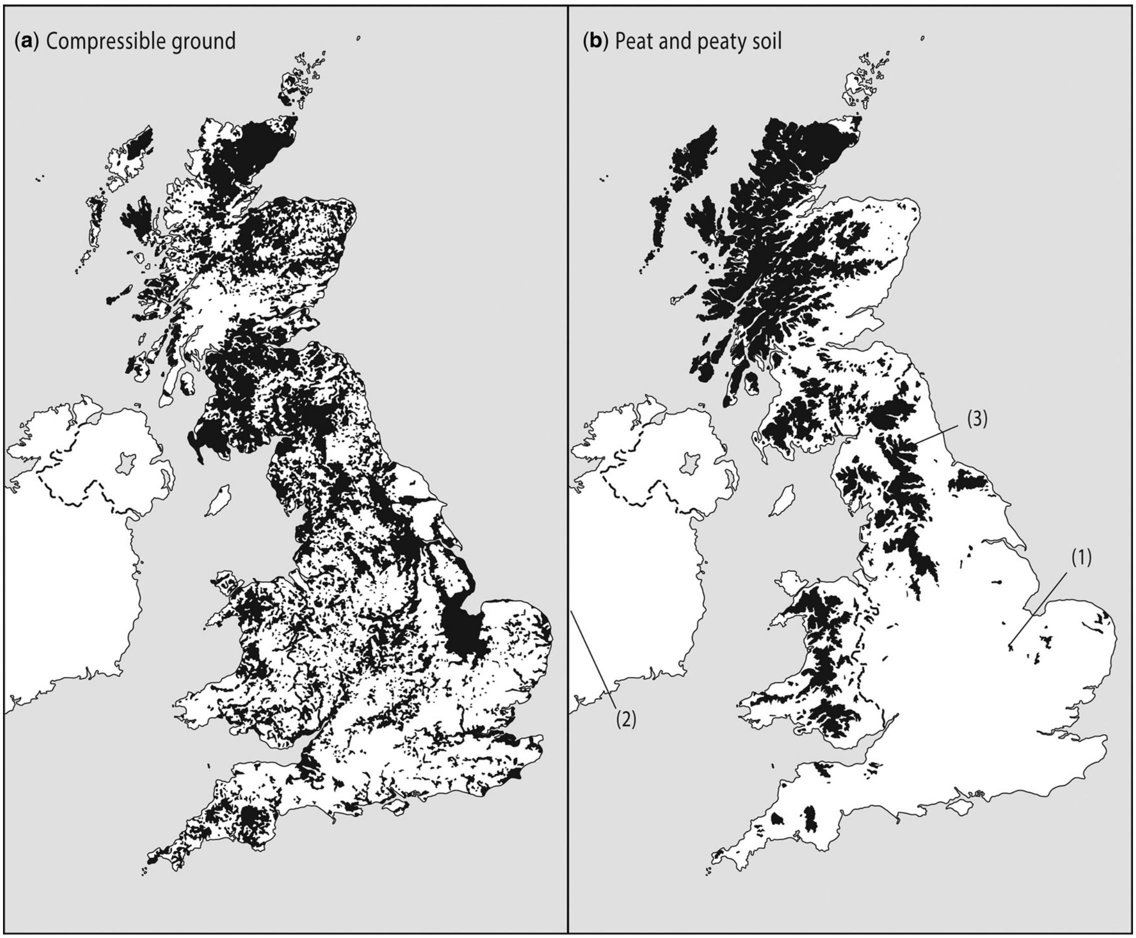

Fig. 1.26. (**a**) Compressible ground potential map and (**b**) peat and peaty soils of the UK (Warburton 2020). Numbers indicate key sites discussed in this volume.

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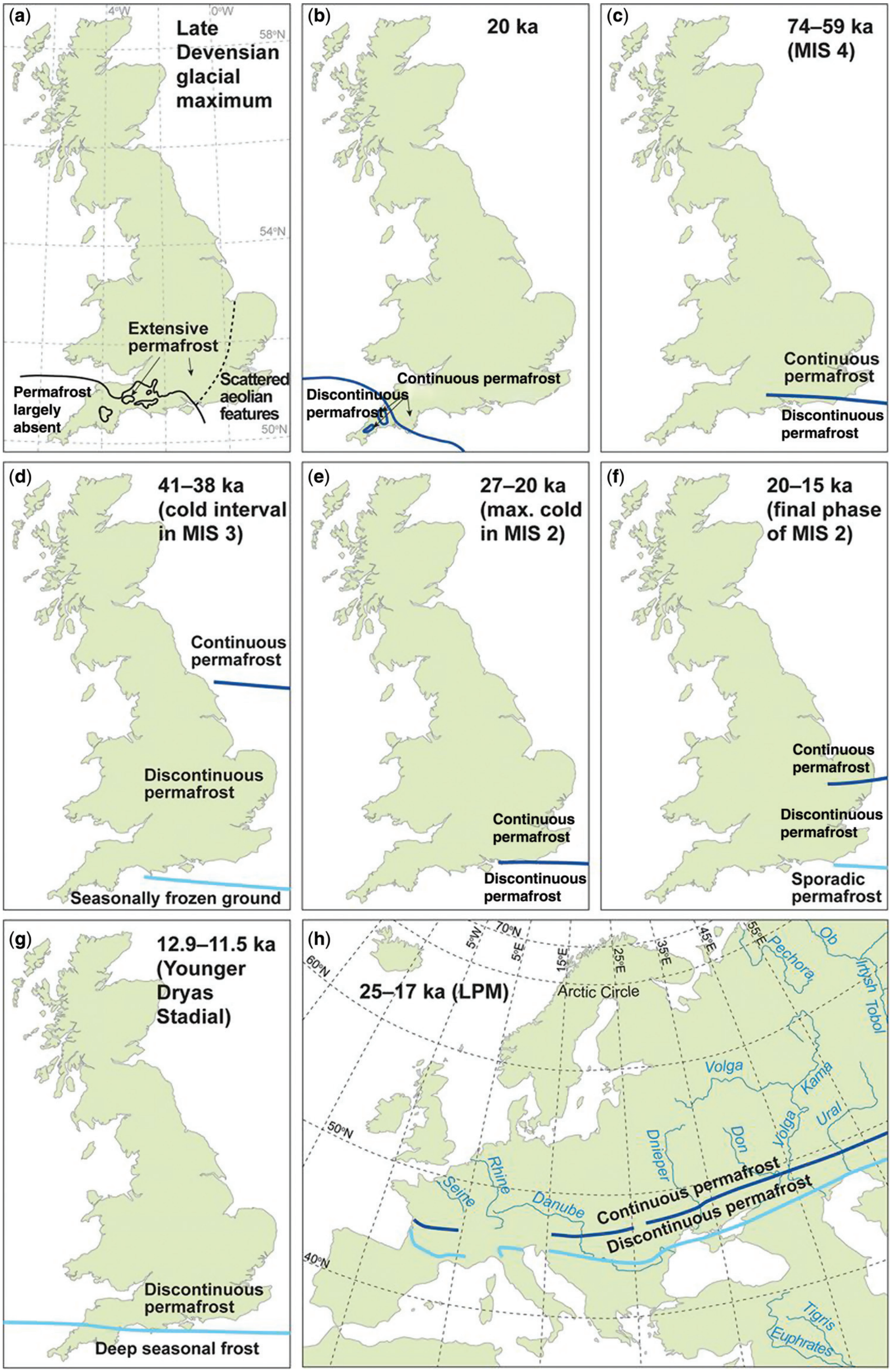

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all parts of the country (Fig. 1.26). Peat accumulates wherever suitable conditions occur such as in areas of high (excess) rainfall and where ground drainage is poor leading to high water tables. In these waterlogged areas, peat develops where the rate of dry vegetative matter accumulation exceeds the rate of decay. Physiochemical and biochemical processes associated with wetland conditions ensure that the accumulating organic matter decays very slowly, safeguarding plant structures that remain partially intact for long periods of time. In the UK, temperate peat accumulates slowly at typically 0.2–1 mm a^{-1}; local rates vary depending on the topography and hydrology of the peat mire.

In the engineering community, peats and organic soils are well known for their high compressibility and long-term settlement and, in terms of engineering properties, peat is notoriously difficult to deal with. The link between the compressibility of peat, its shear strength properties and the risk of bearing capacity failure has not been explored in detail, although the mechanism has been suggested for some peat failures. Peat soils are highly organic, highly compressible and generally possess low undrained strength, and their compression and/or settlement may take a considerable amount of time to stabilize. Estimating the geotechnical properties of peat is difficult because published values are relatively few and the testing of peat using standard geotechnical tests is fraught with problems. Nevertheless, published data suggest that peat in its undisturbed state has little strength with undrained shear strength values typically varying over 5–20 kPa. These values vary with the vegetation composition of the peat (particularly fibre content) and the degree of humification, but are also affected by the method of testing. Given the high compressibility and low strength of peat, local shear failure may occur when compression and/or compaction gives rise to vertical displacements that exceed the shear strength (bearing capacity) of the soil. Shear failure may result where differential displacements of surface peat occur between the area experiencing compression (loading) and the adjacent unloaded peat. In peatlands, such sites typically include: construction embankments or waste heaps; roads and tracks; and foundations such as wind turbine bases. Although such failures are local in origin due to the sensitive nature of peat stability, under the right site conditions these may rapidly propagate to runaway failures.

In engineering practice there is a tendency to either avoid construction on these soils or, if this is not possible, remove or replace the peat material. However, in many countries, including the UK, peat extends over a substantial part of the terrestrial biosphere and peatlands are under increasing pressure for their land use. In lowland areas, particularly in the distal parts of populated deltas and estuaries, peat is common and, due to compaction, may cause land subsidence, resulting in damage to infrastructure and land inundation by the sea.

As part of its UK hazard assessment programme, the British Geological Survey has summarized key information on compressible ground as follows.

> Ground is compressible if an applied load, such as a house, causes the fluid in the pore space between its solid components to be squeezed out causing it to decrease rapidly in thickness (compress). Peat, alluvium and laminated clays are common types of deposits associated with various degrees of compressibility. The deformation of the ground is usually a one-way process that occurs during or soon after construction.

Peat soils are well known for landslide-related hazards and these have been widely reported and documented in the UK and Ireland. However, far less is known about the hazards posed by peat compression and the potential problems associated with this. The aims of this chapter are therefore to: briefly review the engineering background to peat compression; describe the occurrence of peat soils in the UK; provide examples of the compression hazards associated with these deposits; and consider some of the ways these can be mitigated.

1.6.5 Chapter 10: relict periglacial hazards (Berry 2020)

Almost all areas of the UK have experienced the effects of periglaciation and permafrost conditions during the Quaternary (Fig. 1.27) and, as such, relict periglacial geohazards can potentially be a significant technical and commercial risk for many engineering projects. The term periglacial is used here to describe areas affected by cold conditions that border, or have bordered, former Quaternary ice sheets. The term is used here to include processes as well as the resultant sediments, structures and landforms to be found in this relict environment (Ballantyne & Harris 1994; Walker 2005). Periglaciation not only affects the deposits left behind by the various phases of glaciation but also affects older geological strata that were at or near the ground surface. In contrast to present-day periglacial environments, the areal extent of former periglacial environments was much greater. Consequently, relict periglacial features are likely to have once covered the whole of the UK (Walker 2005), including offshore continental shelves of the North Sea, English Channel and Irish Sea.

The aim of this chapter is to describe the specific geological and geotechnical hazards generated from past periglacial processes and to highlight their ground-engineering-related

Fig. 1.27. Maps showing the extent of past permafrost and seasonally frozen ground in the UK (a–g) and Eurasia (h): (**a**) Late Devensian glacial maximum; (b) 20 ka; (c) 74–59 ka (Early Pleniglacial; marine isotope stage (MIS) 4); (d) 41–38 ka (Middle Pleniglacial cold interval in MIS 3); (e) 27–20 ka (maximum cold of the Late Pleniglacial, approximating the Last Glacial Maximum); (f) *c.* 20–15 ka (final phase of the Late Pleniglacial); (g) *c.* 12.9–11.5 ka (Younger Dryas Stadial); and (h) 25–17 ka (Last Permafrost Maximum). Dark blue and light blue lines in (h) indicate southern limits of the continuous and discontinuous permafrost zones, respectively, outside of mountain areas (Murton & Ballantyne 2017).

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legacy in the UK. The potential impacts on engineering are considered if these relict periglacial geohazards are not identified during the investigative phase of the project. The periglacial landsystems classification proposed by Murton & Ballantyne (2017) is adopted to demonstrate its application for the assessment of ground engineering hazards within upland and lowland relict periglacial geomorphological terrains. Techniques for the early identification of the susceptibility of a site to relict periglacial geohazards are discussed, including the increasingly availability of high-quality aerial imagery such as provided by Google Earth that has proved a valuable tool in the identification of relict periglacial geohazards when considered in conjunction with the more usual sources of desk study information (such as geological, geomorphological and topographical reference material).

This chapter summarizes and builds on the landsystem approach developed by a number of authors including Higginbottom & Fookes (1971), Hutchinson (1992), Ballantyne & Harris (1994) and, most recently, the Geological Society Engineering Geology Special Publication 28, *Engineering Geology and Geomorphology of Glaciated and Periglaciated Terrains* edited by Griffiths & Martin (2017). The hierarchical classification system presented in Engineering Geology Special Publication 28 (Murton & Ballantyne 2017) categorizes periglacial processes in terms of upland and lowland terrain systems based on relative elevation. There are four landsystems defined within both upland and lowland terrains: plateaus, sediment-mantled hillslopes, rockslopes and slope–foot landsystems. Two additional landsystems described in lowland terrains only are valley and buried landsystems. The influence of past changes in sea level and its impact on the submergence of land that was previously subject to periglaciation is also considered for marine engineering.

Some periglacial processes and deposits pose a significantly increased geohazard to ground engineering projects due to their location in areas where considerable development activity occurs, such as the South English Midlands. Other periglacial geohazards may be less significant for engineering works, or are significant periglacial geohazards but located beyond the extent of frequent and high-density development, for example in more mountainous terrains in the UK.

This chapter highlights potentially the most significant periglacial geohazards in terms of their risk to civil engineering construction.

1.7 Section D: mining and subsidence hazards

1.7.1 Chapter 11: subsidence resulting from coal mining (Donnelly 2020*b*)

One of the principal geohazards associated with coal mining is subsidence. Coal was originally extracted where it cropped out, then mining became progressively deeper via shallow workings including bellpits that later developed into room-and-pillar workings. By the middle of the 1900s, coal was mined in larger open pits and underground by longwall mining methods. The mining of coal can often result in the subsidence of the ground surface. Generally, there are two main types of subsidence associated with coal mining: the generation of crown holes caused by the collapse of mine entries, mine roadway intersection and the consolidation of shallow voids; and the generation of a subsidence trough as a result of longwall mining encouraging the roof to fail to relieve the strains on the working face. This initiates round movement to migrate upwards and outwards from the seam being mined, and ultimately causes the subsidence and deformation of the ground surface. Methods are available to predict mining subsidence so that existing or proposed structures and land developments may be safeguarded. Ground investigative methods and geotechnical engineering options are also available for sites that have been or may be adversely affected by coal mining subsidence.

Many of the major cities and conurbations owe their existence and expansion to the presence of coal and associated mineral deposits (Fig. 1.28). Coal mining in the UK peaked in 1912–1915, and then experienced a wave of expansion and contraction. The last deep coal mine in the UK closed in December 2015. Coal mining has left behind a legacy of mining hazards (geohazards) that, if not properly managed and investigated, represent a risk to new construction and development. One of these hazards is subsidence. This chapter provides an overview of the occurrence, prediction and control of coal mining subsidence and is aimed at other engineering geologists, geotechnical engineers, civil engineers, planners and developers, as well as those interested in building, construction and the development of land in the abandoned (and those still active) coal mining fields of the UK.

In the context of this chapter, subsidence is considered as the ground movements that occur following the underground mining of coal, mainly the lowering of the ground surface. It should be noted, however, that the coal measures also provided other minerals, such as fireclay, ganister, ironstones, clays, shales, mudstones and sandstones for building purposes. There may be no or only incomplete records of the existence of mine workings, and these can also generate subsidence. The effects of subsidence depend on several factors: the geology, thickness and depth of the coal seam; the mining methods, and in particular the types of roof supports used; the engineering characteristics and behaviours of the strata and soils (superficial deposit); and any mitigative or engineering methods used to reduce the influence of mining subsidence. Coal mining subsidence can have serious, often dramatic and catastrophic, consequences for houses, buildings, engineered structures, underground utilities and services, and agricultural land. The inability to accurately predict the effects of ground subsidence has, in the past, resulted in the sterilization of coal mining reserves in some urban areas. This was partly associated with the expected subsidence compensation costs for damage to land, houses, roads and structures.

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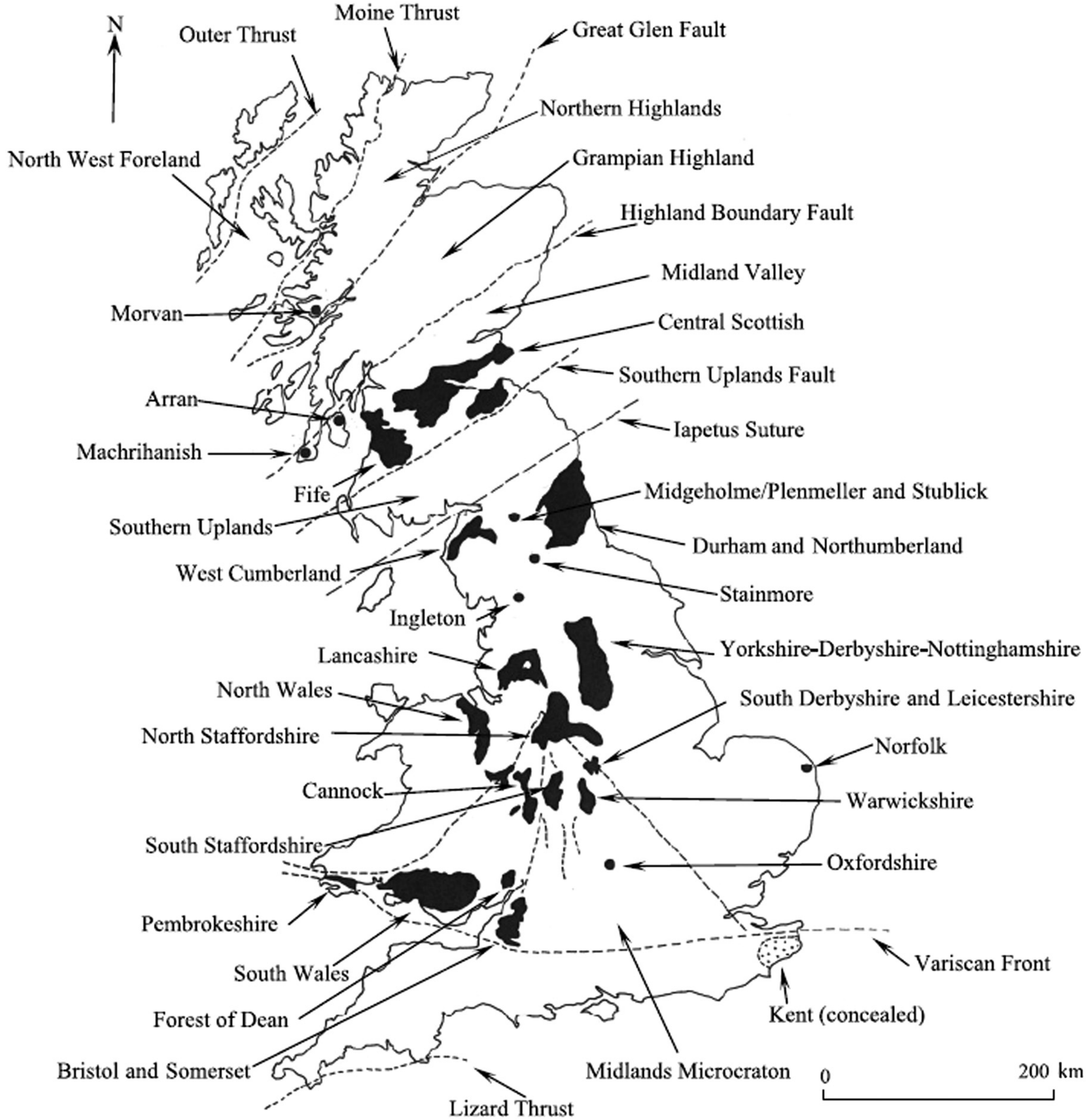

Fig. 1.28. Map showing the general tectonic structure of the British Isles and the location of the main coalfields (Donnelly 2006).

1.7.2 Chapter 12: subsidence resulting from chalk and flint mining (Edmonds 2020*b*)

Old chalk and flint mine workings occur widely across southern and eastern England. Over 3500 mines are recorded in the national Mining Cavities Database held by Peter Brett Associates LLP, and more are being discovered each year. The oldest flint mines date from the Neolithic period onwards and the oldest chalk mines from at least medieval, possibly even Roman, times. The most intensive period for mining was during the 1800s, although some mining continued into the 1900s. The size, shape and extent of the mines vary considerably, with some types being found only in particular areas. They range from crudely excavated bellpits to more extensive pillar-and-stall styles of mining (Fig. 1.29). The mines were created for a series of industrial,

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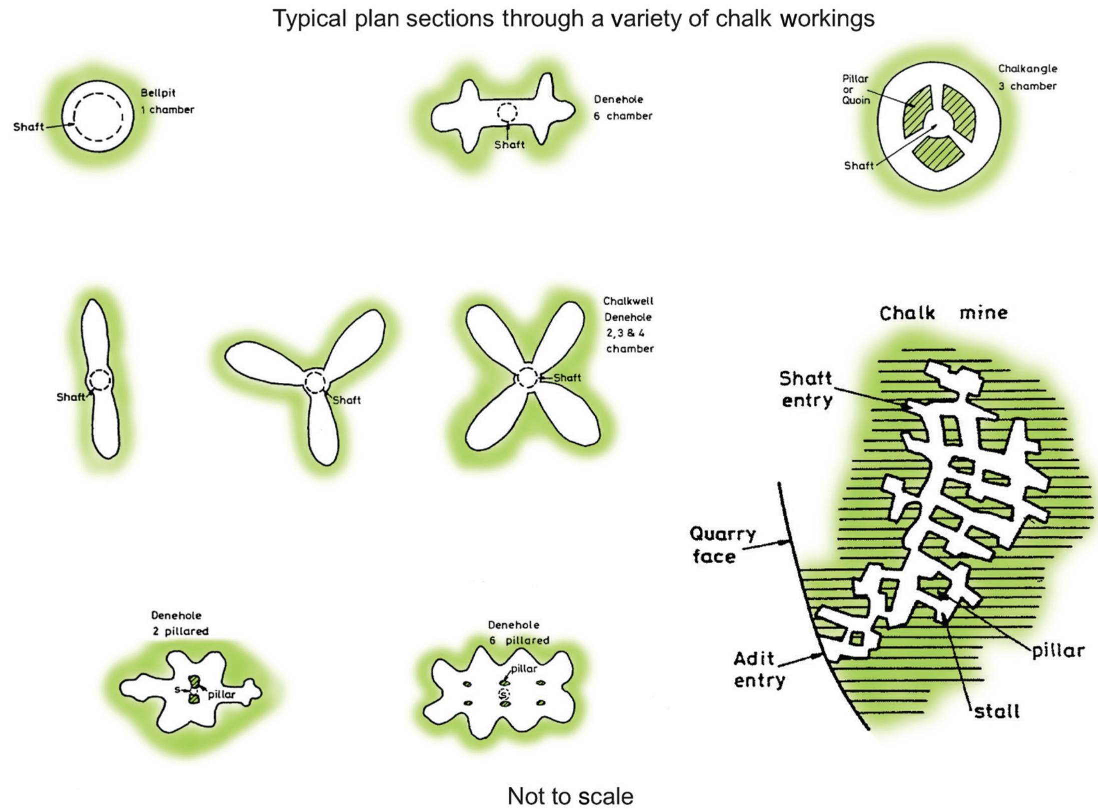

Fig. 1.29. Typical schematic plan sections through a variety of chalk mine workings (Edmonds 2020*b*).

building and agricultural purposes. Mining locations were not formally recorded, so most are discovered following collapse of the ground over poorly backfilled shafts and adits. Many of the old chalk mine workings were left open on abandonment, with just their shaft or adit entrances filled and sealed. The locations of abandoned mines are not well recorded so they pose a serious ground subsidence hazard, particularly since most of the old mines lie within 10–20 m of the ground surface. As urban development extends outwards around the historical centres of towns and cities, construction activities are revealing more mines each year as collapse of the ground occurs.

The subsidence activity, often triggered by heavy rainfall or leaking water services, poses a hazard to the built environment and people. Purpose-designed ground investigations are needed to map the mine workings and carry out follow-on ground stabilization after subsidence events. Where mine workings can be safely entered, they can sometimes be stabilized by reinforcement rather than infilling.

1.7.2.1 Flint mine workings

Flint mine workings may be referred to as ancient or modern workings. The earliest ancient workings date from the Neolithic period (*c.* 4000–2500 BC) and the later workings date from the Iron Age (from *c.* 800 BC to AD 100) or Roman period (*c.* AD 43–409). Some mines may also date from the medieval period (*c.* AD 600–1485).

1.7.2.2 Chalk mine workings

Chalk mine workings also have quite a long history, possibly from Roman times onwards. Mining styles show regional variation and both simple and more complex mine forms appear to co-exist through time, including features such as bellpits, deneholes, chalkwells, chalkangles and pillar-and-stall mines.

1.7.3 Chapter 13: hazards associated with mining and mineral exploitation in Cornwall and Devon, SW England (Gamble *et al.* 2020)

The importance of mining in the history of Cornwall is demonstrated by the county hosting the second oldest geological society in the world (established 1814), and with Cornwall and West Devon being selected in 2006 as a World Heritage Site by UNESCO for its mining landscape. The World Heritage designation was specifically related to the long history of

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metallic mining (mainly copper, tin and arsenic) in Cornwall and West Devon. However, while the last Cornish tin mine closed in 1998 (South Crofty), the *10th Edition of the Directory of Mines and Quarries* listed nearly 70 active mines in Cornwall and Devon that were still extracting and processing china clay, china clay waste, clay and shale (including ball clay), igneous and metamorphic rocks, sandstone, sea salt, silica sand, slate, and tungsten, and there was even a small tin streaming operation. In Cornwall, china clay alone has yielded 165 Mt of marketable clay since mining began in the mid-eighteenth century. Today, mining remains an integral part of the West Country economy, not least now because the heritage of mining is a source of revenue from tourism. Cornwall and Devon can be considered as exceptional in the UK for their long history of mining (suggested as starting in Phoenician times, i.e. *c.* 1550–300 BC), the temporal and spatial coverage of its mining infrastructure, its changing history of mineral exploitation, the range of mining-related hazards, and the nature and extent of remedial works that have been undertaken.

In this chapter, the geological basis for the mining industry in Cornwall and Devon is briefly summarized followed by a description of the history of mining and the environmental consequences. Approaches to assessing the hazards associated with mining are examined along with the varied methods of remediation, with reference made to case studies that demonstrate the various facets of the mining heritage of Cornwall and Devon.

1.7.4 Chapter 14: geological hazards from salt mining and brine extraction (Cooper 2020*b*)

In the UK rock salt (halite or sodium chloride) is present in Triassic and Permian rocks, from which it has been exploited for several millennia. Rock salt is not only a valuable industrial commodity, but also a highly soluble material responsible for natural and anthropogenic subsidence geohazards. The Triassic salt-bearing strata are widespread in the Cheshire basin area, but also common in parts of Lancashire, Worcestershire, Staffordshire and Northern Ireland (Fig. 1.30). Permian saliferous rocks are mainly present in the NE of England. This chapter considers the occurrence of salt deposits, and the way they either dissolve naturally or have been extracted by mining and anthropogenic dissolution. Subsidence problems that have arisen and continue to occur are highlighted, and methods of mitigating the problems by planning and construction/remediation techniques are considered.

Like table salt, rock salt is highly soluble and dissolves very quickly in water to make brine. This process occurs naturally in the UK, meaning that salt is not seen anywhere at outcrop. It is instead present in the subsurface, where the upper part of the sequence is dissolved, producing a buried dissolution surface (salt karst) overlain by collapsed and foundered strata. The natural dissolution processes and groundwater flow are evidenced by the presence of brine springs, many of which have been known and exploited

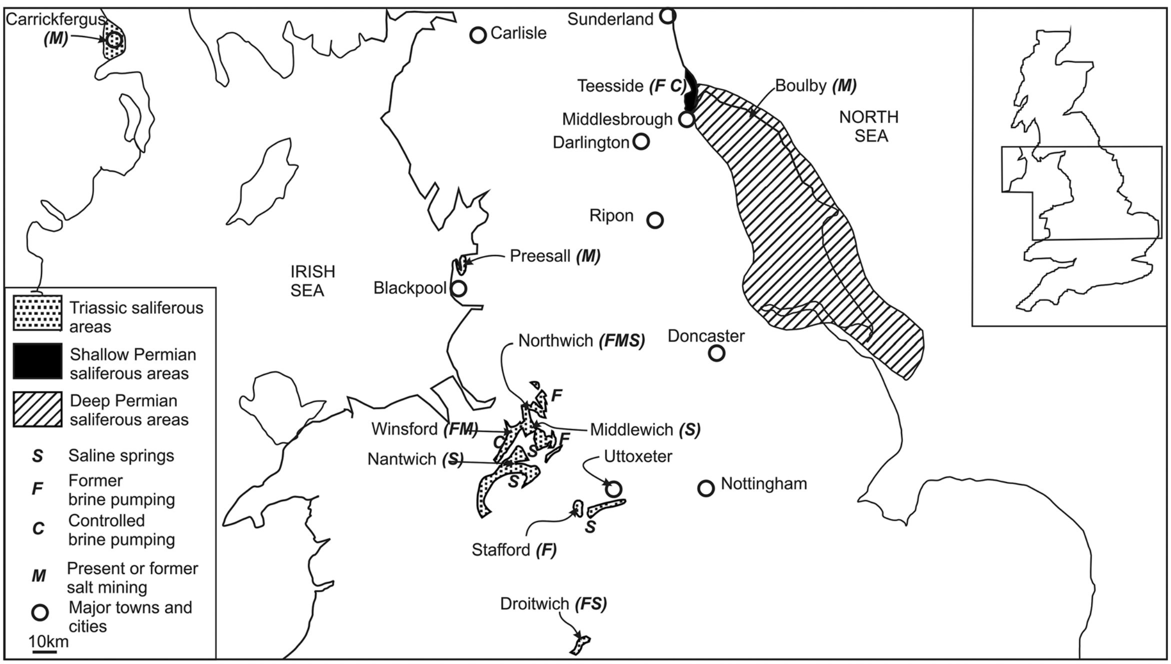

Fig. 1.30. Distribution of salt deposits in the UK showing mined and brine pumping areas (Cooper 2020*b*).

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since Roman times. Through the Middle Ages these springs were moderately exploited and gave rise to place names ending in 'wych' or 'wich'. However, it was in Victorian times that large-scale extraction both by mining and brine extraction accelerated, leading to some large and devastating instances of catastrophic subsidence. The UK is still dealing with this legacy and the effects of subsequent brine and rock salt extraction in many places, especially in parts of Cheshire, Droitwich, Stafford and Preesall. Where shallow brine extraction has occurred it mimics the natural salt karstification processes, and the results of natural and anthropogenic events can be difficult to differentiate. In Northern Ireland the salt has been mined traditionally by pillar-and-stall mining. In certain cases severe subsidence has occurred due to water ingress into the mines, causing dissolution of the pillars and catastrophic collapse.

Permian salt occurs at depth beneath coastal Yorkshire and Teesside. Here the salt deposits and the karstification processes are much deeper than in the Triassic salt, and the salt deposits are bounded up-dip by a dissolution front and collapse monocline. Salt has been won from these Permian rocks by dissolution mining, and some historical to recent subsidence due to brine extraction has occurred along the banks of the River Tees and to the NE of Middlesbrough.

Modern pillar-and-stall salt mining is deeper than old Victorian mining and located in mudstone and salt sequences that are completely dry. Modern brine extraction is controlled and restricted to deep-engineered cavities that are kept full of brine on completion, or used for other storage such as gas or waste; both methods of extraction have low or zero risks of subsidence.

1.7.5 Chapter 15: geological hazards from carbonate dissolution (Edmonds 2020*b*)

The dissolution of limestone and chalk (soluble carbonates) through geological time can lead to the creation of naturally formed cavities in the rock. The cavities can be air, water, rock or soil infilled and can occur at shallow levels within the carbonate rock surface or at deeper levels below. Depending upon the geological sequence, as the cavities break down and become unstable, they can cause overlying rock strata to settle and tilt, and the collapse of non-cemented strata and superficial deposits as voids migrate upwards to the surface. Natural cavities can be present in a stable or potentially unstable condition. The latter may be disturbed and triggered to cause ground instability by the action of percolating water, loading or vibration. The outcrops of various limestones and chalk occur widely across the UK (Fig. 1.31), posing a significant subsidence hazard to existing and new land development and people. In addition to subsidence, they can also create a variety of other problems such as slope instability or the generation of pathways for pollutants and soil gas to travel along, and impact all manner of engineering works. Knowledge of natural cavities is essential for planning, development control and the construction of safe development.

Limestone and chalk are composed of calcium carbonate that is soluble in the presence of acidic water. Rainwater combines with atmospheric and biogenic carbon dioxide to form weak carbonic acid that then dissolves the calcium carbonate. Where the water table level lies at depth within the carbonate sequence, the water can enter into the rock via joints and fissures to percolate downwards and cause dissolution. The effects of dissolution tend to be concentrated within the upper surface zone of the rock, especially where permeable overlying deposits are present. The cover deposits influence the acidity and concentration of water flows penetrating the carbonate rock surface. As solution features are formed over time, the cover deposits will tend to settle and collapse down into the enlarging features, often leading to subsidence occurring at the ground surface that can cause damage to buildings and infrastructure in urban areas.

For new construction, the challenge is to check whether solution features are present below a site and to understand the karst geohazard setting to ensure that the correct engineering solutions are put in place to permit safe development. This includes not only addressing the safe support of buildings, roads and services, but also the effects of surface water drainage disposal. Unfortunately, there are many cases where the design of development has not taken karst into account, resulting in subsidence damage. Following a subsidence event, it is essential to identify the nature and cause of movement before a suitable remedial solution to stabilize the ground can be executed. Property evacuation may be necessary for safety reasons before the remedial works can be completed and, in some instances, an economic solution might not be feasible. Blighting and dereliction of property can be an arising issue in certain circumstances.

The typical range of natural cavity forms found in limestone and chalk is shown in Figure 1.32. Where low-permeability cover deposits are present at the surface, surface water drainage will tend to collect to form streams that flow across the land surface until they meet the exposed outcrop of the limestone or chalk. At this location the water dissolves the rock surface, leading to the creation of solution-widened joints and bedding planes. As these develop, the water readily enters and flows down into the rock mass to form an underground drainage network. Over time, a depression is formed at the surface where the overland flow disappears, which is referred to as a swallow hole. In places where permeable cover deposits occur over the limestone and chalk, the water will tend to be absorbed into the surface in a diffuse manner and swallow holes are less prevalent. Given sufficient time, dissolution of joints at the surface of a limestone will tend to form linear features that extend to depth, widening upwards. Where the bare limestone surface expression of the intersecting dissolution along joints is revealed at the surface, they are known as limestone pavements. When dissolution is concentrated at the intersection of joints, a point feature may be formed centred on the intersection that becomes pipe shaped with time extending to depth. Pipe-shaped features are commonly associated with chalk

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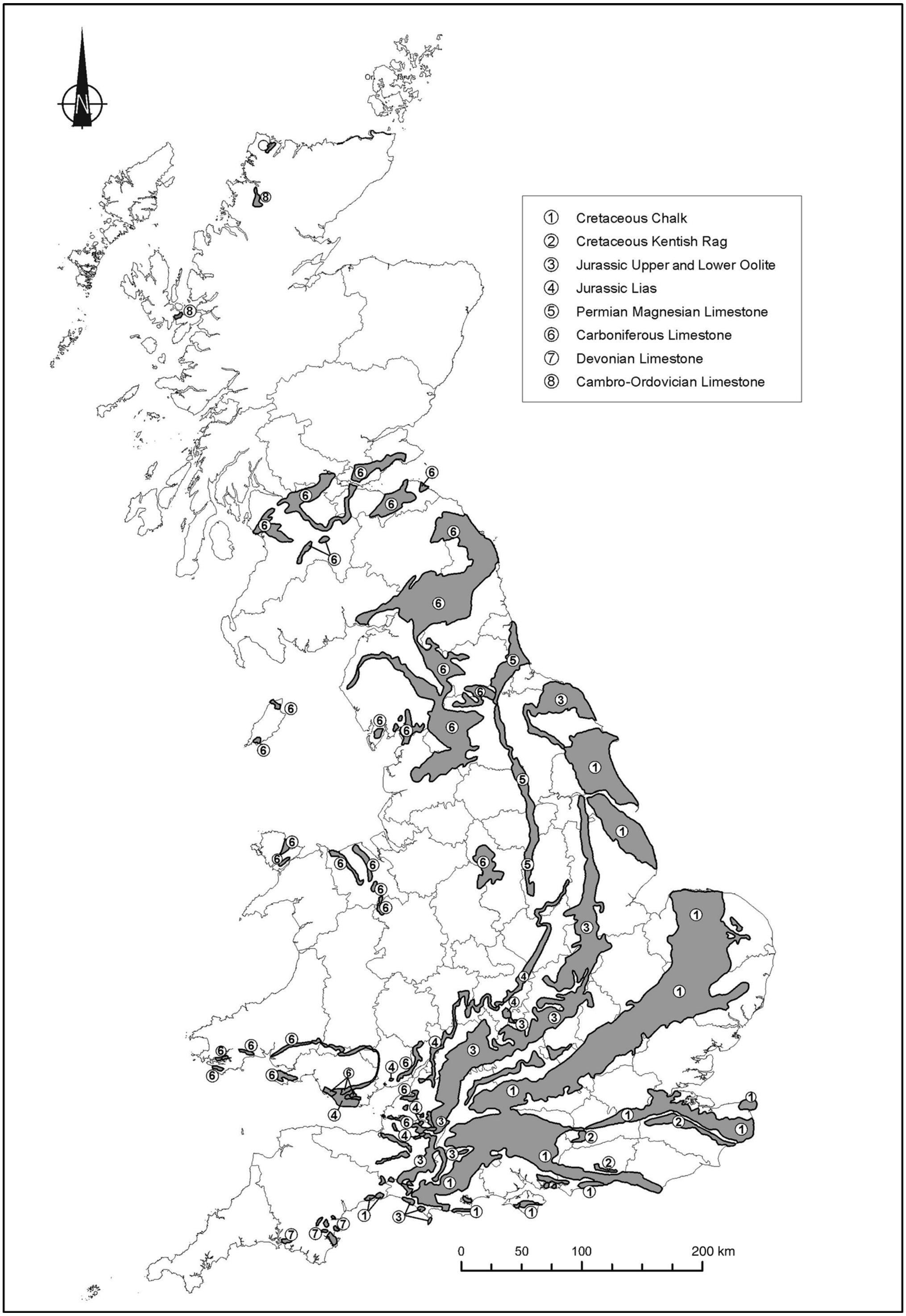

Fig. 1.31. The spatial distribution of soluble carbonate rocks in the UK (**Edmonds 2020*b***).

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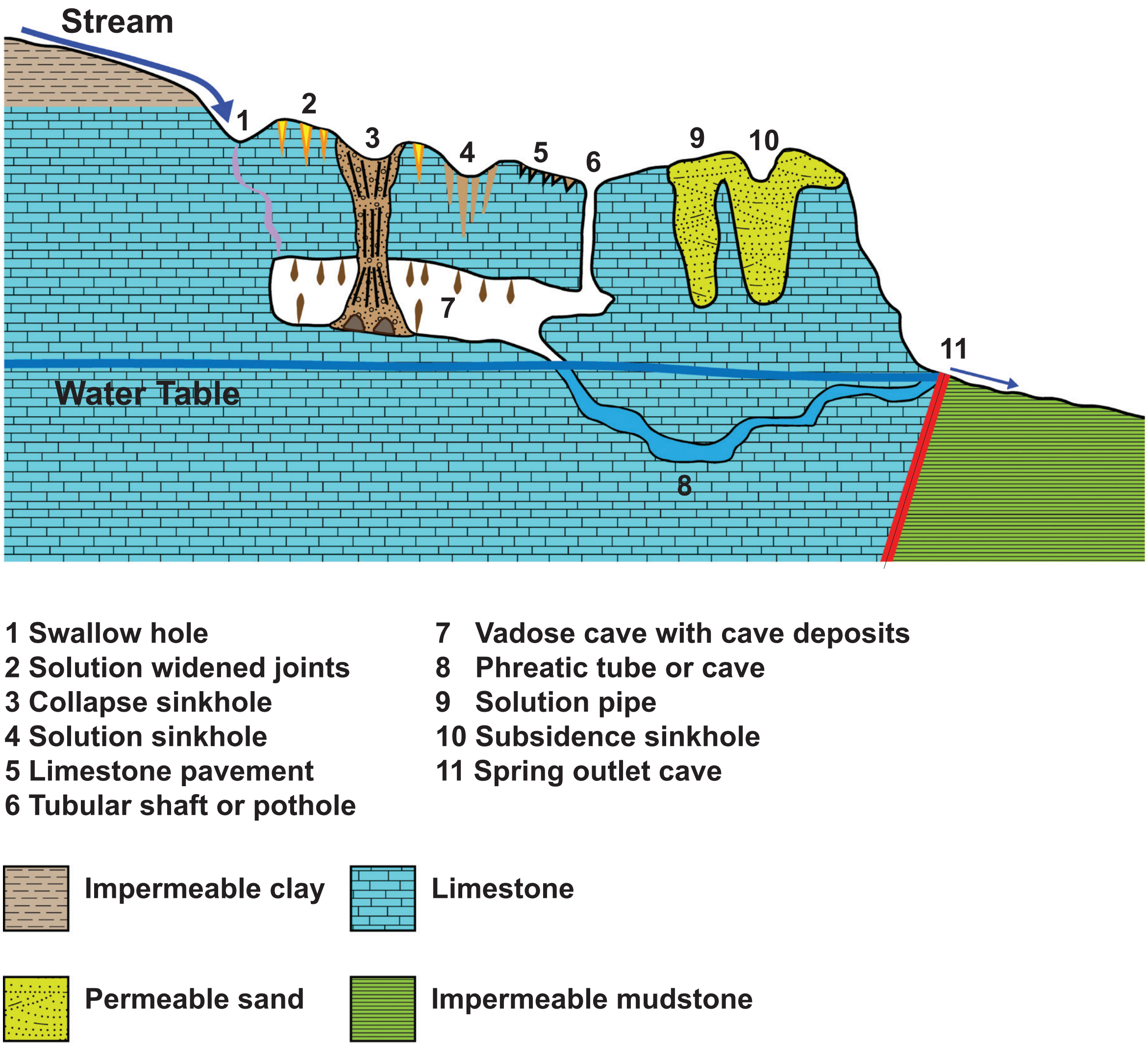

Fig. 1.32. Range of natural cavity types formed on limestone and chalk (Edmonds 2020*a*).

and referred to as solution pipes. The subsurface shape of solution pipes formed in chalk can sometimes be irregular and voided. It is common for overlying cover deposits or rocks to settle down into the enlarging cavities being formed. This leads to downwards ravelling of deposits and the development of soil arches that can suddenly collapse, causing subsidence at the surface above. The surface hollows formed are referred to as subsidence sinkholes. Where cover deposits are absent, surface hollows can be created by dissolution alone of the limestone surface, focused on the pattern of joints present or along a fault plane; these surface hollows are referred to as solution sinkholes.

1.7.6 Chapter 16: geological hazards caused by gypsum and anhydrite in the UK: dissolution, subsidence, sinkholes and heave (Cooper 2020*b*)

Gypsum and anhydrite are both soluble minerals that form rocks that can dissolve at the surface and underground, producing sulphate karst and causing geological hazards, especially subsidence and sinkholes. The dissolution rates of these minerals are rapid and cavities and/or caves can enlarge and collapse on a human timescale. In addition, the hydration and recrystallization of anhydrite to gypsum can cause considerable expansion and pressures capable of causing uplift

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and heave. Sulphate-rich water associated with the deposits can react with concrete and be problematic for construction. This chapter reviews the occurrence of these rocks in the near surface of the UK (Fig. 1.33) and looks at methods for mitigating, avoiding and planning for their associated problems.

Gypsum, hydrated calcium sulphate ($CaSO_4.2H_2O$), is attractive as satin spar, beautiful as carved alabaster and practical as plasterboard (wallboard) and plaster. However, gypsum is highly soluble and a cause of geological hazards capable of causing severe subsidence to houses, roads, bridges and other infrastructure. Gypsum dissolves rapidly and, where this occurs underground, results in caves that evolve and quickly enlarge, commonly leading to subsidence and sometimes to catastrophic collapse. Gypsum is mostly a secondary mineral and is present in the UK mainly as fibrous gypsum (satin spar) and alabastrine gypsum (alabaster) that may include large crystals and aggregates of crystals. It occurs near the surface passing into anhydrite, the dehydrated form ($CaSO_4$) at depths below about 40–120 m, depending on the local geology and water circulation. The hydration of anhydrite to gypsum in the subsurface causes expansion and heave, problematic to engineering and hydrogeological installations such as ground source heat pumps. Furthermore, gypsum, especially in engineering fills, can react with cement causing heave. Gypsum and anhydrite

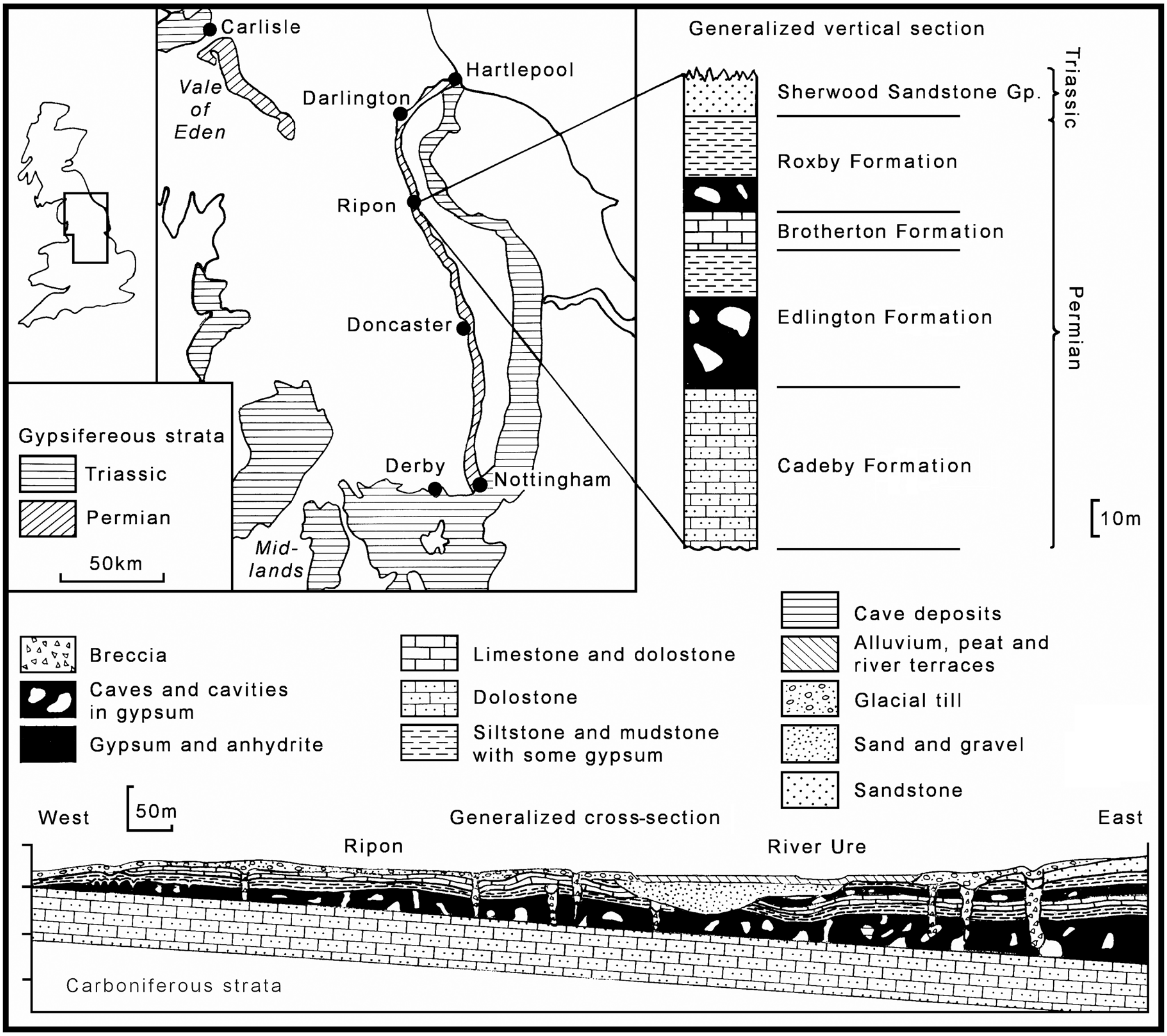

Fig. 1.33. Regional geology of the Permian and Triassic gypsiferous sequences with a cross-section from west to east through the Ripon area showing the E-dipping dolomite and gypsum sequence cut into by the glacial valley of the River Ure (Cooper 2020*a*).

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are present in the Triassic strata of the Midlands and SW of the UK and in the Permian strata of the NE and NW of England (Fig. 1.30). In all these areas various geological hazards are associated with these rocks, the most visible being subsidence and sinkholes. Gypsum and anhydrite also occur to a small extent in the Jurassic of southern England, but no specific problems have been reported related to these deposits.

Gypsum dissolves more readily in flowing water; next to rivers, this can be at a rate of about 100 times faster than that seen for limestone dissolution. Under suitable groundwater flow conditions, caves in gypsum can enlarge at a rapid rate and result in large chambers. Collapse of these chambers produces breccia pipes that propagate through the overlying strata to break through at the surface and form subsidence hollows (Fig. 1.34).

1.7.7 Chapter 17: mining-induced fault reactivation in the UK (Donnelly 2020*b*)

Faults are susceptible to reactivation during coal mining subsidence. The effects may be the generation of a scarp along the ground surface, which may or may not be accompanied by associated ground deformation including fissuring or compression. Reactivated faults vary considerably in their occurrence, height, length and geometry. Some reactivated faults may not be recognizable along the ground surface, known only to those who have measured the ground movements or who are familiar with the associated subtle ground deformations. By comparison, other reactivated faults generate scarps up to several metres high and many kilometres long, often accompanied by widespread fissuring of the ground surface. Reactivated faults induced by mining

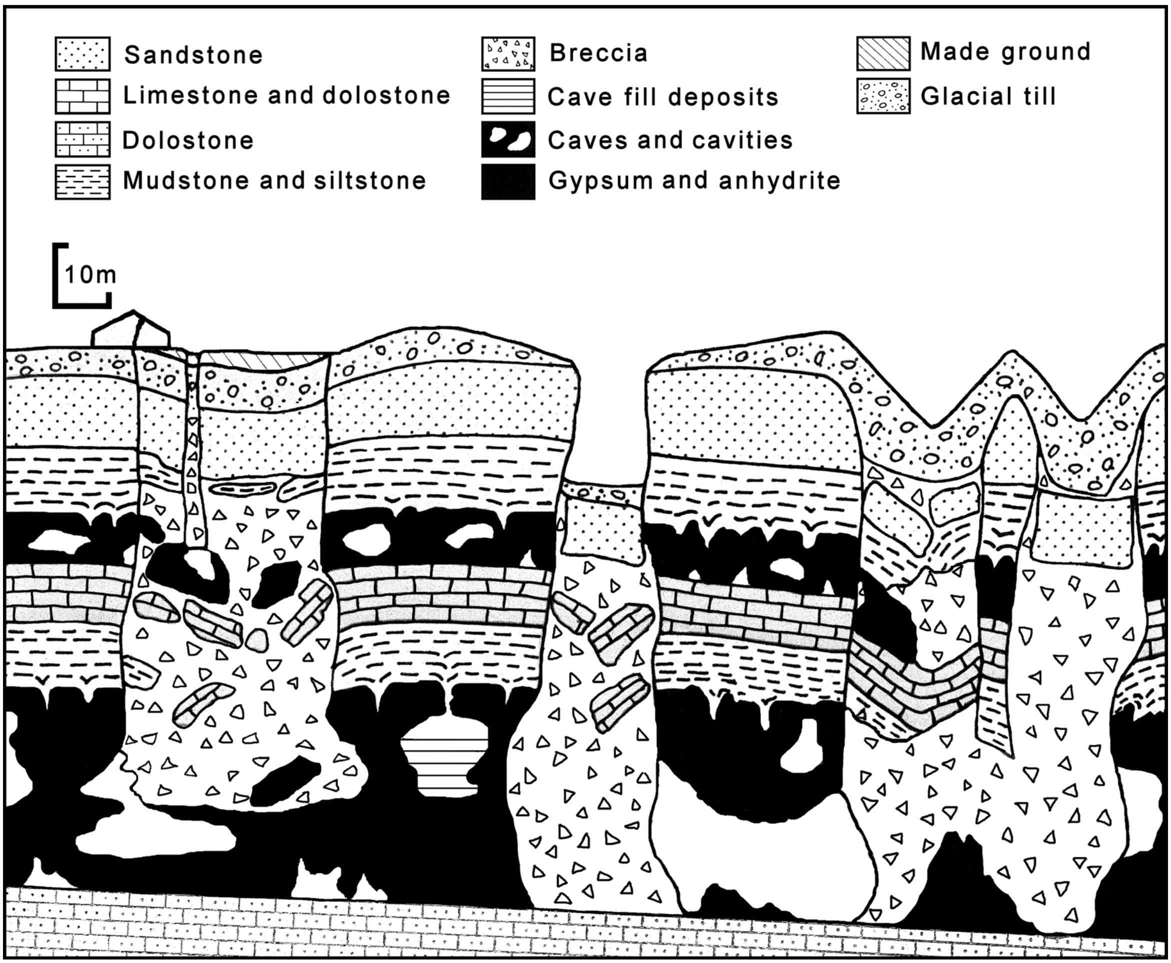

Fig. 1.34. Stylized cross-section through gypsum dissolution subsidence features in the east of the Ripon subsidence belt (Cooper 2020*a*).

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subsidence have caused damage to roads, structures and land. The objective of this chapter is to provide a general overview of the occurrence and characteristics of fault reactivation in the UK.

Various documents and publications are available to assist with the prediction of coal mining subsidence; however, faults located in areas prone to coal mining subsidence are susceptible to reactivation, and this cannot be forecast. Reactivated faults may result in the generation of a scarp, graben, fissure or compression hump along the ground surface (Fig. 1.35).

Fault reactivation has been documented in the UK since the middle of the 1800s. However, many of the earlier theories on fault reactivation were somewhat speculative and lacked a fundamental geological appreciation of fault mechanisms. During the 1950s and later, increased mining subsidence compensation claims provided the incentive for the British coal mining industry to investigate fault reactivation. However, by the 1980s the exact mechanisms of fault reactivation still remained unclear, although numerous cases had been documented. As a result, some coal resources, particularly those located in densely populated parts of the UK, were effectively sterilized, since it was not possible to predict the ground movements and to estimate the potential compensation claims. In the 1990s, following continued cases of fault reactivation, recommendations from government (The Commission on Energy & The Environment 1981) resulted in further research to investigate fault reactivation. As with all faults, it is still not possible to predict exactly if, when and where a fault may reactivate when subjected to mining subsidence. However, this research has now enabled the factors that control fault reactivation and the different styles of ground deformation to be better understood.

1.8 Section E: gas hazards

1.8.1 Chapter 18: radon gas hazard (Appleton 2020)

Radon is a natural radioactive gas that cannot be seen, smelt or tasted by humans and can only be detected with special equipment. It is produced by the radioactive decay of radium, which in turn is derived from the radioactive decay of uranium. Uranium is found in small quantities in all soils and rocks, although the amount varies from place to place. There are three naturally occurring radon (Rn) isotopes: ^{219}Rn (actinon), ^{220}Rn (thoron) and ^{222}Rn, which is commonly called radon. ^{222}Rn (radon) is the main radon isotope of concern to people. ^{220}Rn has been recorded in houses, and about 4% of the average total radiation dose for a member of the UK population is from this source.

There are a number of different ways to quantify radon. These include (1) the radioactivity of radon gas; (2) the dose to living tissue, for example, to the lungs, from solid decay products of radon gas; and (3) the exposure caused by the presence of radon gas. The average radon concentration in houses in the UK is 20 Bq m^{-3}.

The dose equivalent indicates the potential of harm to particular human tissues by different radiations, irrespective of their type or energy. The average person in the UK receives an annual effective radiation dose, which is the sum of doses to body tissues weighted for tissue sensitivity and radiation weighting factors, of 2.8 mSv, of which about 85% is from natural sources: cosmic rays, terrestrial gamma rays, the decay products of ^{220}Rn and ^{222}Rn, and the natural radionuclides in the body ingested through food and drink. Of this natural radiation, the major proportion is from geological sources.

Mapped bedrock geology explains on average 25% of the variation of indoor radon in England and Wales, while mapped superficial geology explains, on average, an additional 2%. In the UK, relatively high concentrations of radon are associated with particular types of bedrock and unconsolidated deposits, for example, some granites, uranium-enriched phosphatic rocks and black shales, limestones, sedimentary ironstones, permeable sandstones and uraniferous metamorphic rocks. Permeable superficial deposits, especially those derived from uranium-bearing rock, may also be radon prone. Geological units associated with the highest levels of naturally occurring radon (Fig. 1.36) are: (1) granites in SW England, the Grampian and Helmsdale districts of Scotland and the Mourne Mountains in Northern Ireland; (2) Carboniferous limestones throughout the UK and some Carboniferous shales in northern England and Wales; (3) sedimentary ironstone formations in the English Midlands; (4) some Ordovician and Silurian mudstones, siltstones and greywackes in Wales, Northern Ireland and the southern uplands of Scotland; (5) Middle Old Red Sandstone of NE Scotland; and (6) Neoproterozoic psammites, semipelites and meta-limestones in the western sector of Northern Ireland.

1.8.2 Chapter 19: methane gas hazard (Wilson & Mortimer 2020)

This chapter identifies potential sources, and the key chemical properties, of methane. Guidance is provided on deriving a conceptual site model for methane, utilizing various lines of evidence to inform a robust, scientific, reasoned and logical assessment of associated gas risk. Discussion is provided regarding the legislative context of permanent gas risk assessment for methane, including via qualitative, semi-quantitative and detailed quantitative (including finite element modelling) techniques. Strategies for mitigating risks associated with methane are also outlined, together with the legal context for consideration of methane both in relation to the planning regime and under Part 2A of the Environmental Protection Act 1990.

Methane (historically known as ‘marsh gas’) was discovered in 1776 by Alessandro Volta, who collected gas bubbles from disturbed sediments on Lake Maggiore. Methane is the most abundant organic compound in the Earth’s atmosphere. Its occurrences in the Earth’s crust are predominantly of biogenic origin (i.e. it is formed by bacterial decomposition of

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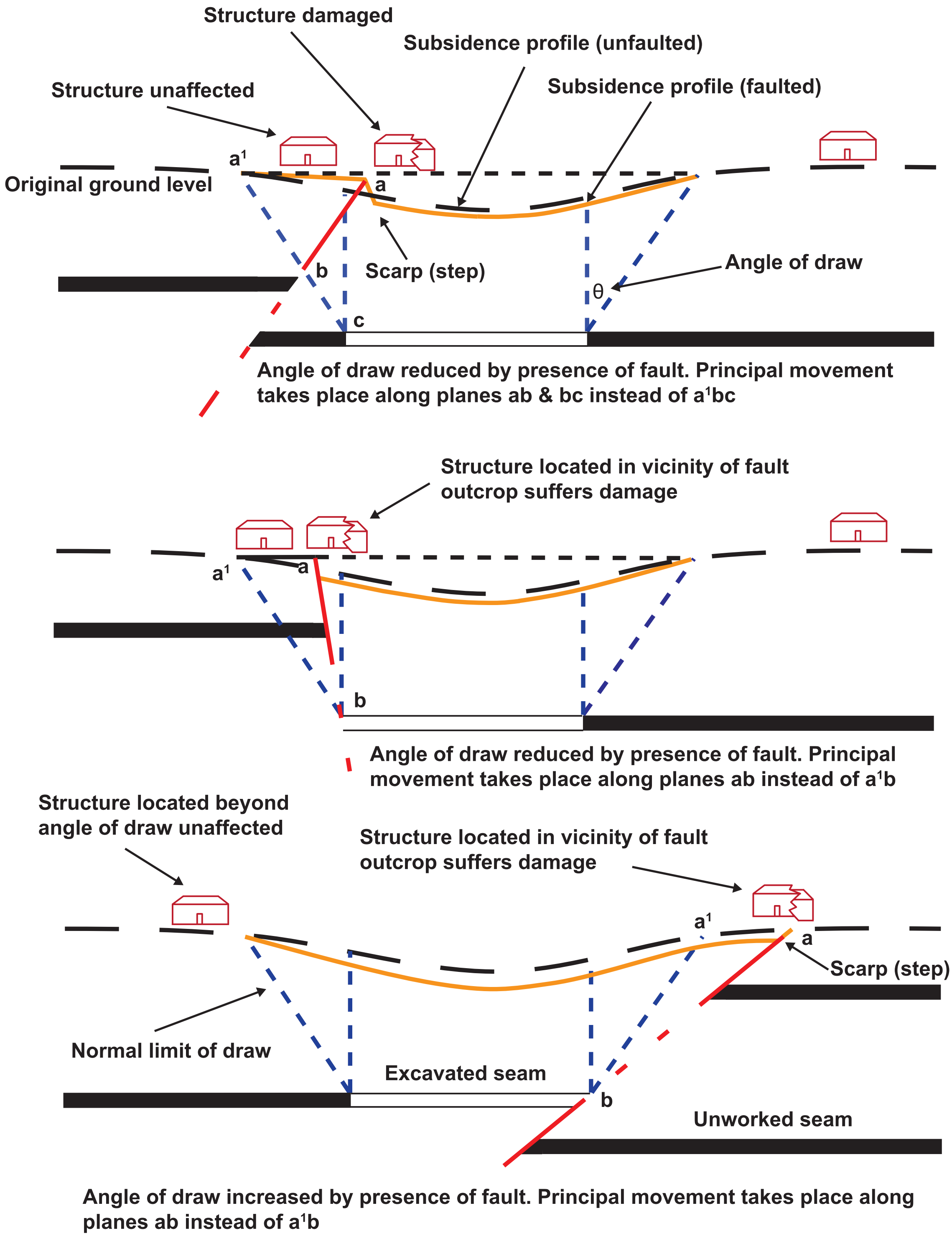

Fig. 1.35. The influence of faults on mining subsidence and the angle-of-draw (Donnelly 2020*a*).

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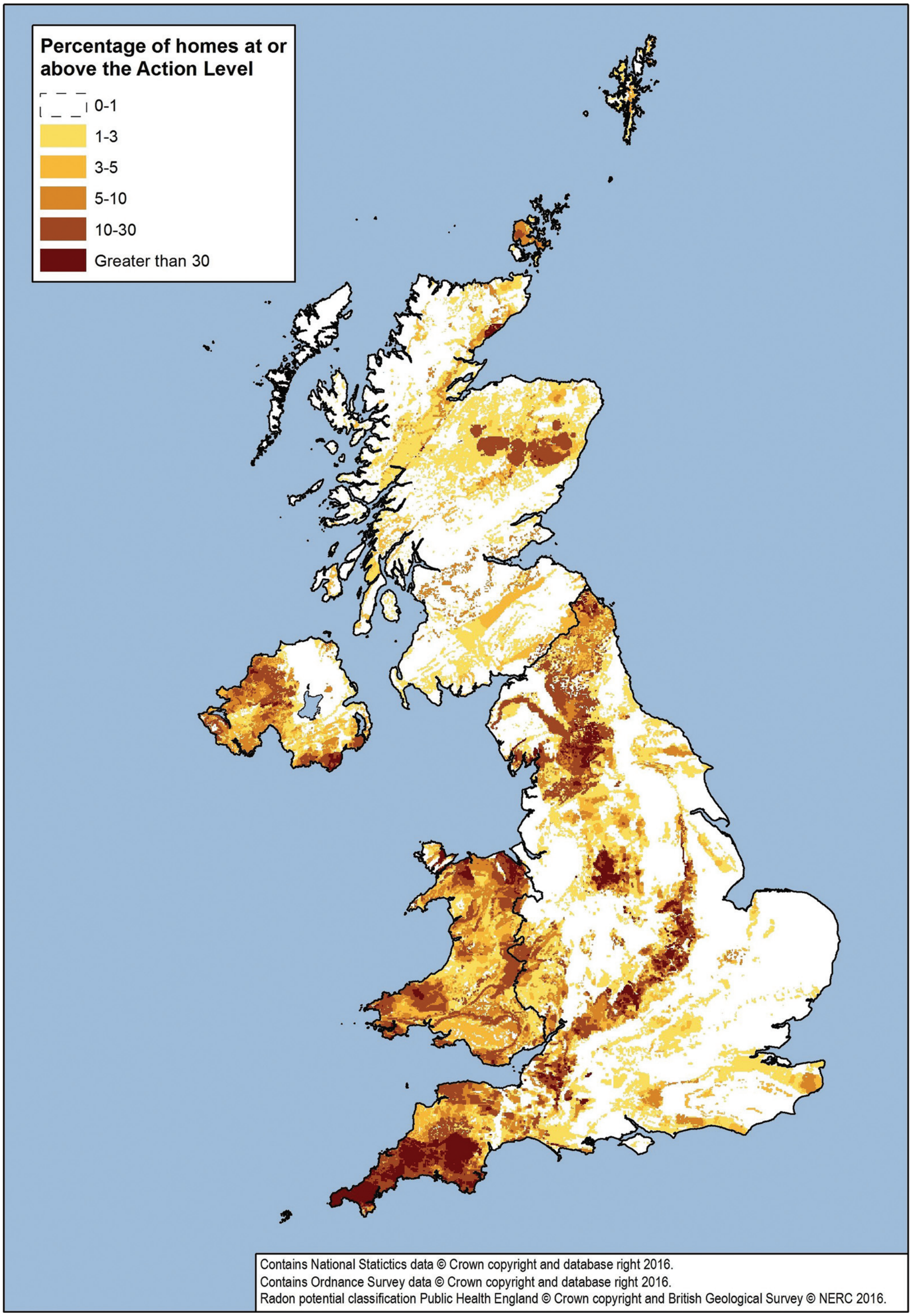

Fig. 1.36. Radon potential map of England and Wales (Appleton 2020).

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organic matter). Methane can also be formed by decomposition of organic matter as a result of geothermal heat and/or pressure, when it is known as thermogenic gas. Such gas is generated at great depth, but the methane can migrate to the surface along faults or other features and accumulate in near-surface rocks. Abiogenic methane is thought to be formed by chemical reactions, for example during cooling of magma or serpentinization of ultramafic rocks. Methane has been detected in many shallow drift deposits in UK soils where there is no apparent external source such as landfill. It is thought that the methane occurs from disturbances caused by installing monitoring wells, and the oxidation of small volumes of organic material in the soils to produce carbon dioxide that is subsequently reduced by methanogens. This low-level source of methane is not known to pose a hazard to developments. Methane is ubiquitous in the subsurface environment and is present in soils and rocks below many parts of the UK and other countries. Methane is often present at elevated concentrations in uncontrolled and engineered fill materials in the unsaturated zone, especially where the soil is wet, and an anaerobic zone exists below the groundwater.

The greatest hazard posed by methane is that it is flammable and/or explosive. If an explosive mix occurs in a building, tunnel or mine, for example, there is a risk of explosion. Generally, the lower explosive limit (LEL) of methane is 5% by volume in air and the upper explosive limit (UEL) is 15% by volume in air. The explosive limits of methane will change as the oxygen concentration reduces. When carbon dioxide reaches 25% concentration, or nitrogen reduces to 36%, methane is not flammable. In addition to the explosive and/or flammable hazard posed by methane, at concentrations in excess of 33% by volume it may also act as an asphyxiant by displacing oxygen. Typically, physiological effects are observed when oxygen concentrations fall below 18% by volume. Displacement of oxygen at the root ball can also result in phytotoxic effects to plants and vegetation.

Conclusions

The UK is perhaps unique globally in that it presents almost the full spectrum of geological time, stratigraphy and associated lithologies within its boundaries. With this wide range of geological assemblages comes the full range of geological hazards, whether geophysical, geotechnical, geochemical or related to georesources. An awareness of these hazards and the risks that they pose is a key requirement of the engineering geologist. This volume has set out to define and explain these key hazards, to detail their detection, monitoring and management, and to provide a basis for further research and understanding.

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