BRITISH GEOLOGICAL SURVEY

TECHNICAL REPORT WA/97/35

A geological background for planning and development in the Afon Teifi catchment

Authors

R A Waters, J R Davies, D Wilson and J K Prigmore

Contributors

R M Carruthers, B C Chacksfield, L M Coleby, J R Hallam, R E Heaven, P R N Hobbs, K J Northmore, N S Robins, S J Self, P Shand and P R Wilby

Keywords

Afon Teifi, south-west Wales, geology, planning and development

Front cover

Afon Teifi at Cenarth [2692 4160]

Bibliographical reference

R A Waters, J R Davies, D Wilson and J K Prigmore. 1997. A geological background for planning and development in the Afon Teifi catchment. *British Geological Survey Technical Report*, WA/97/35. 102pp.

Keyworth, Nottingham British Geological Survey 1997

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British Geological Survey offices

Keyworth, Nottingham NG12 5GG
☎ 0115–936 3100 Fax 0115–936 3200
e-mail: sales @bgs.ac.uk
www.bgs.ac.uk
Online shop: www.geologyshop.com

Murchison House, West Mains Road, Edinburgh EH9 3LA
☎ 0131–667 1000 Fax 0131–668 2683
e-mail: scotsales@bgs.ac.uk

London Information Office at the Natural History Museum (Earth Galleries), Exhibition Road, South Kensington, London SW7 2DE
☎ 020–7589 4090 Fax 020–7584 8270
☎ 020–7942 5344/45 e-mail: bgslondon@bgs.ac.uk

Forde House, Park Five Business Centre, Harrier Way, Sowton, Exeter, Devon EX2 7HU
☎ 01392–445271 Fax 01392–445371

Geological Survey of Northern Ireland, 20 College Gardens, Belfast BT9 6BS
☎ 028–9066 6595 Fax 028–9066 2835

Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB
☎ 01491–838800 Fax 01491–692345

Sophia House, 28 Cathedral Road, Cardiff, CF11 9LJ
☎ 029–2066 0147 Fax 029–2066 0159

Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon, Wiltshire SN2 1EU
☎ 01793–411500 Fax 01793–411501

Acknowledgements

The project leader was R A Waters, BGS, Thematic Mapping and Onshore Survey Division, under the programme manager T J Charsley and the direction of a steering group of the cofunding local authorities. The report was compiled and edited by R A Waters. J R Davies wrote the sections on the geological and geomorphological background, drift deposits and solid geology. D Wilson wrote the introduction and the section on mineral deposits. The engineering geology was undertaken by P R N Hobbs, J R Hallam and S J Self; the engineering properties section was was written by K Northmore, D Wilson and J R Davies and Appendix 4 by P R N Hobbs. The landslips and slope steepness section was written by J R Davies and D Wilson; the slope steepness map was generated by H Baxendale and J Walsby. The hydrogeology was undertaken by N S Robins, P Shand and L M Coleby; the hydrogeology and flood limits section was written by N S Robins, P Shand and J R Davies. This section benefited from the advice provided by W Davies, S Neale and A Irvine of the Environment Agency (Wales). Geophysical work was undertaken by R M Carruthers, B C Chacksfield and R E Heaven, who also wrote Appendix 4. P R Wilby supervised the drilling programme and logged the boreholes.

We acknowledge the help provided by holders of data in permiting the transfer of the records to the National Geoscience Recordss Centre, BGS, Keyworth. BGS is especially grateful for the assistance provided by the local authorities, the Environment Agency (Wales), Sir William Halcrow and Partners Ltd, W S Atkins Ltd and many other civil engineering consultants. The cooperation of landowners, tenants and quarry companies in permitting access to their land is gratefully appreciated.

In particular the help and advice provided by the members of the Project Steering Group is acknowledged. The Steering Group comprised the following: P Kendall, R Meade, M Miles, S Thomas (Carmarthen County Council); S Coker, E Williams (Pembrokeshire County Council); G Dorrington, A Pykett, G Williams (Cyngor Sir Ceredigion); R Green (the former Dyfed County Council).

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Executive summary

This report presents the results of a geological mapping and earth science research project carried out by the British Geological Survey (BGS) in the Afon Teifi catchment. The work was undertaken between 1995 and 1997, and was co-funded by BGS, Carmarthenshire County Council, Cyngor Sir Ceredigion, Pembrokeshire County Council and the Environment Agency (Wales). The principal aim was to provide up-to-date geological maps, and report on geological factors relevant to planning and development.

The report summarises previous geological work in the area, and provides a description of the geology and geomorphology of the region based on the mapping. The report focuses on the description and inferences, that can be drawn from six thematic maps, designed to address the main issues relevant to land use in the area. The maps are for use by planners and engineers, and should be used with reference to relevant sections of this report. The maps are as follows:

Thematic Map 1: Drift deposits

Thematic Map 2: Solid geology

Thematic Map 3: Mineral deposits and surface mineral workings

Thematic Map 4: Engineering properties

Thematic Map 5: Hydrogeology and flood limits

Thematic Map 6: Landslips and slope steepness

Copies of the report and maps can be obtained from the British Geological Survey, Kingsley Dunham Centre, Keyworth, Nottingham NG12 5GG. Archival data are held at the same address.

Limitations

This report aims to provide a general introduction to the geological factors relevant to planning and development in the Afon Teifi catchment, and background information essential for desk studies and site investigations. The report and associated thematic maps provide information, which is interpretive, of variable quality and unevenly distributed. Other data may exist, which was not available to the project, which would have added to the information shown on the maps and included in the report.

This report, and associated maps, provides only general indications of ground conditions and must not be relied upon as a source of detailed information about specific areas, or as a substitute for site investigations or ground surveys. Users must seek appropriate professional advice and, if necessary, carry out site investigations and ground surveys, to ensure that ground conditions are suitable for any particular land use or development.

The study area

The mapped area (Figure 1) is of irregular outline, reflecting the form of the Teifi valley and its tributaries. It extends from Cemaes Head, on the Cardigan Bay coast, 37 km inland to Ffos-y-ffin, 2 km east of Lampeter; and from Ferwig, Blaenannerch and Aberbedw, in the north, to Cwmorgan and Pencader, in the south, covering over 300 km^2 of the catchment. About sixty percent of the project area lies in the county of Ceredigion, thirty percent lies in Carmarthenshire and the remaining ten percent in Pembrokeshire. The area is predominantly rural, with agriculture and tourism dominating the local economy. The principal towns of the region are Cardigan, Newcastle Emlyn, Llandysul, Llanybydder and Lampeter, which are the main sites of light industry. The westernmost part of the project area lies within the Pembrokeshire National Park.

Sources of information

The information used in this study was acquired from numerous sources. The project area was geologically surveyed at 1:10 000 scale and the resulting geological maps underpin many of the thematic products of the project. Additional sources of information were aerial photographs, borehole and trial pit records, site investigation data, hydrogeological and hydrological data, and library references. Lists of some of these data sources are provided.

Geology

The solid rocks (bedrock) of the catchment comprise a sedimentary succession, over five kilometres thick, dominantly composed of mudstones, with some siltstones and sandstones. These rocks were deposited between 450 and 420 million years ago, during the Ordovician and Silurian periods. They were subsequently folded, faulted and uplifted during the Caledonian Orogeny.

Over much of the area, solid rocks are overlain by poorly consolidated drift (superficial) deposits. These comprise Quaternary glacial deposits, including till (boulder clay), glaciofluvial sand and gravel and glaciolacustrine clays and silts, as well as periglacial or post-glacial deposits such as head, peat, alluvium, alluvial fan deposits, river terrace deposits and tidal river deposits. Drift deposits locally exceed 70 m in thickness, but such cases are restricted to buried valleys. Man-made deposits locally overlie both the bedrock and drift deposits.

Details of the nature and thickness of the natural drift and artificial (man-made) deposits, and the solid rocks, are presented in sections of the report covering Thematic Maps 1 and 2 respectively.

Mineral resources

The distribution of potential bulk mineral deposits, and sites of active or disused workings in these materials are shown on Thematic Map 3. Sand and gravel deposits are widespread and may be an important regional resource. They have been accurately surveyed and both good and poor quality materials have been distinguished. Planning factors which may limit their exploitation have not been assessed. Glaciolacustrine clay deposits were formerly worked as brick clays and for mixing with coal dust in the manufacture of inferior fuel. They have been used, and may have economic potential as, a lining agent for landfill sites. The solid rocks of the area are a source of building stone, roadstone and rock fill.

Engineering ground conditions

The report discusses the nature and properties of the common engineering soil types and solid rocks in the project area. The distribution of these materials together with a summary of their engineering properties are shown on Thematic Map 4. Potentially difficult ground conditions may result from areas of soft ground associated with some drift deposits, including glaciolacustrine clays, alluvium and peat, and with the weathering of bedrock. The suitability of bedrock and superficial deposits as foundations, as engineered fill and their excavatability are discussed. The report summarises measures required to identify potential problems and to permit safe development of sites.

Hydrogeology and flood limits

The report presents data on the physical and chemical properties of groundwater within the catchment, and discusses issues associated with the abstraction and quality of both surface water and groundwater. The nature and distribution of the principal aquifers and their vulnerability to pollution are addressed on Thematic Map 5. The floodplains of the Afon Teifi and its tributaries have been mapped in detail and, in conjunction with data provided by the Environment Agency, provide a framework for both assessing and managing flood risk throughout the catchment.

Landslips and slope steepness

Landslips were systematically mapped and their distribution is shown on Thematic Map 6, together with slope steepness data. There is, on average, only one landslip per square kilometre. Steep slopes in superficial deposits have the highest potential for slope instability. Nearly half the mapped landslips are associated with Glaciolacustrine clay deposits. About a third of the landslips mapped are currently active. This report identifies the principal factors leading to landslips, and indicates measures which should be undertaken to ensure that future development does not cause slope failure.

References, glossary and appendices

This report contains a comprehensive reference list and glossary of technical terms. Appendices provide information on borehole and geotechnical data sources, the geophysical investigations, drilling programme, geotechnical database, and quarries and bulk mineral workings.

1 Introduction

This report presents the results of a two year geological mapping and earth science research project, on the Afon Teifi catchment between Cardigan Bay and Lampeter. The work was equally funded by the British Geological Survey (BGS) and a consortium of local authorities, and the Environment Agency (Wales). The project was initiated prior to the recent reorganisation of Welsh local authorities, at which point, it was funded by Carmarthen, Ceredigion and Preseli Pembroke district councils, and the former Dyfed County Council. Following reorganisation, local authority funding was provided by Carmarthen County Council, Cyngor Sir Ceredigion and Pembrokeshire County Council.

1.1 BACKGROUND TO THE PROJECT

Recent research in the USA (Bernknopf et al., 1993) has demonstrated that modern geological maps, in facilitating cost effective resource and waste management, site investigation and road and building design, can result in savings to both the public and private sectors, amounting to four times the cost of the survey itself, within a five year period following publication.

The relevance of geological maps to land use planning and development is given formal recognition in the planning guidance notes issued by the Department of the Environment on minerals and unstable land (Department of the Environment, 1989; 1990), and in the scope of its earth science research programmes. Over the last decade these have included several BGS geological mapping projects in the industrialised regions of Wales and England. The aim of these projects was to develop map-based products and databases, designed to present geological information in a form tailored to the needs of local authorities. Areas in Wales for which BGS has produced such thematic (or environmental) maps include the Bridgend district (Wilson and Smith, 1985), Deeside (Campbell and Hains, 1988) and the Wrexham urban area (Hains, 1991). The Bradford area (C N Waters et al., 1997) is one of several comparable examples in England.

Geological maps provide data on ground conditions which is essential for safe, cost effective site investigation and construction. They locate potential sand and gravel, hard rock aggregate and other mineral resources, they delineate flood-prone land, and they identify geohazards such as landslips and mine entrances. Geological maps are valuable to hydrogeologists in locating sources of groundwater and in assessing the susceptibility of local aquifers to pollution, thus providing data vital to effective waste management. They are also used by the Welsh Office, Agriculture Developmemt and Advisory Service for the categorisation of agricultural land. Therefore, geological maps and accompanying geological and geotechnical reports provide a framework for effective land use planning and development; this is as necessary in rural areas as it is in urban and industrialised regions.

The project area falls within a broad sector of central Wales for which the only systematic geological maps previously available, date from reconnaissance surveys, undertaken at the one-inch scale during the middle of the nineteenth century. These maps fall well short of modern user requirements in that they fail to depict features such as drift deposits, landslips, many solid rock divisions, mineral workings, waste tips and flood-prone land. However, recent events in the region, such as the St Dogmaels Landslip, ground instability in Newcastle Emlyn, the 1987 flood of the upper reaches of the Teifi valley, and contested planning applications for mineral aggregate extraction and waste disposal sites, have highlighted the urgent need for detailed, up-to-date geological map coverage.

In 1994, the BGS put forward a costed proposal to survey part of the Afon Teifi catchment, inviting contributions from the local authorities and the Environment Agency (Wales), then the National Rivers Authority. The scope and area of the proposed survey reflected a combination of scientific, geographical and political factors. It encompassed the predicted distribution of certain categories of superficial deposits, so as to address the land instability problems identified by all three local authorities in their regions. It offered an early opportunity to assess potential sand and gravel resource areas around Cardigan and Lampeter, identified in the recent Department of the Environment/Welsh Office commissioned appraisal of sand and gravel resources in South Wales (Crimes and Lucas, 1992). Studying the majority of a catchment meant that the project fitted in with the river catchments initiative of the Environment Agency. Critically, the inclusion of parts of three local authority regions within the proposed survey area allowed the costs of the project to be shared. The local authorities agreed to cofund the project in 1995; the Environment Agency (Wales) offered funding in 1996.

1.2 OBJECTIVES

The principal aims of the project were three-fold:

- To geologically survey the designated area at 1:10 000 scale and to present this data in the form of BGS 1:25 000 scale geological maps.
- To provide the earth science information resulting from the project in a form understandable to non-geologists in the local authorities, the Environment Agency and other interested bodies. This was to be achieved by:

  i A series of thematic maps, designed to present aspects of the geological data in ways which address particular landuse issues such as mineral planning, ground instability, engineering conditions and aquifer vulnerability.

  ii An explanatory Technical Report which, in addition to providing general planning guidance, was to address specific geological issues which were of concern to the local authorities and the Environment Agency in the Teifi valley. In formulating these products, the project was to build on the example of earlier BGS/Department of the Environment studies in support of local land use planning in Wales and England.

- To provide a modern geological framework for the region, which would underpin any future scientific or applied research into the geology, engineering geology and hydrogeology by private or public sector organisations.

1.3 PROJECT AREA

The area specified for geological survey was that part of the Afon Teifi catchment which lay below the 120 m contour, an area of around 250 km^2 (Figure 1). For practical reasons, substantial areas above 120 m were also surveyed, so that at the completion of the project, geological maps for over 300 km^2 of the catchment had been produced. The mapped area includes parts of eight 1:25 000 scale Ordnance Survey maps. It extends from Cemaes Head, on the Cardigan Bay coast, 37 km inland to Ffos-y-ffin, 2 km east of Lampeter; and from Ferwig, Blaenannerch and Aberbedw, in the north, to Cwmorgan and Pencader, in the south. It ranges from low water mark in the Teifi Estuary to a high point of 220 m at Coedeiddig, to the south of Cwmann. About sixty percent of the project area lies in the county of Ceredigion, thirty percent in Carmarthenshire and the remaining ten percent in Pembrokeshire. The area is predominantly rural, with agriculture and tourism dominanting the local economy. The principal towns are Cardigan, Newcastle Emlyn, Llandysul, Llanybydder and Lampeter and these are the main sites of light industry in the region. The westernmost part of the project area, between Poppit and Cemaes Head, lies within the Pembrokeshire National Park.

1.4 METHODOLOGY AND SOURCES OF INFORMATION

The main investigative procedures used during the project were:

Ground surveying

The whole of the project area was geologically surveyed at 1:10 000 scale. This involved the logging of natural and temporary exposures in both solid rocks and superficial deposits, and the detailed surveying and interpretation of landscape features with the aid of aerial photographs. Hand augers were used as an aid to delineate and categorise superficial deposits. Data gathered during the field survey was recorded on 1:10 000 scale field slips, which will eventually be archived, and made available for inspection at the BGS National Geoscience Records Centre (NGRC), Nottingham.

Collection and databasing of borehole, trial pit and geotechnical data

Although such data considerably enhance the understanding of subsurface geology, they are generally sparse in rural areas. Prior to the initiation of the project, the number of borehole and trial pit records held by the NGRC for the project area totalled 71, while the number of site investigation reports numbered seven. By actively seeking data from the local authorities, from public bodies including Welsh Water and the Environment Agency, and from site investigation companies and geotechnical consultants, the borehole and trial pit database has been expanded to 278 items, and the site investigation reports to 40. Even so, the distribution of data within the area is very uneven, being concentrated in areas where development has already occurred, in the towns and along major roads. Lists of geotechnical reports and borehole information obtained for the catchment area are given in Appendix 1, and geotechnical testing results are collated in Appendix 4. Data on groundwater sources and flooding was provided by the Environment Agency.

Review of scientific and geotechnical literature

A comprehensive literature search of published scientific and technical sources has been undertaken. Pertinent, unpublished PhD and MSc theses were also examined. A comprehensive bibliography is provided at the end of this report.

Geophysical investigations

A total of eight gravity and 14 resistivity traverses have provided data on the depth and fill of abandoned and buried segments of the Teifi Valley between Cardigan and Rhuddlan. An account of these investigations is provided in Appendix 2.

Drilling

Two cored boreholes have been drilled to investigate the fill of the abandoned segments of the Teifi valley, to provide calibration for the geophysical traverses, and to provide material for engineering testing. The BGS Cardigan No.1 (Llwynpiod) Borehole [1786 4769], west of Cardigan, proved a sequence of superficial deposits 79 m thick. Rockhead in the borehole was at -38.7 m OD. The BGS Cardigan No.2 (Pen-y-bryn) Borehole [1759 4284], west of Cilgerran, penetrated 68 m of superficial deposits with rockhead at -29.3 m OD. Details of the drilling methods and results are given in Appendix 3.

Groundwater sampling

Over 50 spring, well or borehole sites were sampled for chemical analysis of groundwaters. Physical measurements of water table surfaces and data on rates of flow were also obtained.

1.5 PRESENTATION OF RESULTS

The results of the project are presented in two parts: a series of geological maps, and a technical report, including a set of thematic maps for use in land use planning and development

Geological maps

The results of the geological mapping are included on eight 1:25 000 scale geology maps comprising parts of the following Ordnance Survey sheets:

SN 14	SN 23	SN 24	SN 33
SN 34	SN 43	SN 44	SN 54

These maps display much of the complex primary geological data from which the thematic maps are derived. They constitute part of the published BGS large scale geological map coverage of the UK landmass. Copies can be ordered from the British Geological Survey, Kingsley Dunham Centre, Keyworth, Nottingham, NG12 5GG.

Technical Report

This report provides a comprehensive review of earlier scientific and geotechnical studies of the solid rocks and superficial deposits of the region. It describes the geology of the surveyed area and summarises the scientific findings of the survey. However, it focuses principally on the description of the six 1:50 000 scale thematic maps. These maps are designed to highlight aspects of the geology, which have a direct bearing on land use planning and development in the Afon Teifi catchment. The topics addressed by these maps are:

Drift deposits
Solid geology
Mineral deposits and surface mineral workings
Engineering properties
Hydrogeology and flood limits
Landslips and slope steepness

1.6 USES AND LIMITATIONS OF THE DATA

This report, and associated maps, provides only a general indication of ground conditions and must not be relied upon as a source of detailed information about specific areas, or as a substitute for detailed site specific investigations or ground surveys. Users are advised to seek appropriate professional advice and, if necessary, carry out site investigations and ground surveys, to ensure that ground conditions are suitable for any particular land use or development.

This report and its thematic maps are intended to provide general information on earth science factors which are relevant to land use planning and sustainable development in the Afon Teifi region. Much of this information is interpretative and is based on data of variable quality and uneven distribution. The report reflects the limitations of that data. All boundaries shown on the various maps should be regarded as approximate. Whilst every effort has been made to collect a representative range of relevant data, some information may not have been accessed. Localised or anomalous features and conditions may not be represented in the data. No information made available after 31st March 1997 has been taken into account. New information is continually being acquired, and users of the report and maps are advised to check carefully for additional relevant information, particularly when considering the characteristics and suitability of specific sites.

This report and thematic maps are mainly aimed at the non-geologist. However, the use of some specialist geological terms has been necessary, and a glossary of these is provided. The individual thematic maps assume some specialist planning or technical knowledge. Each map has only a limited key, and it is essential that the maps are used in conjunction with the appropriate section of the report, where more detailed descriptions are

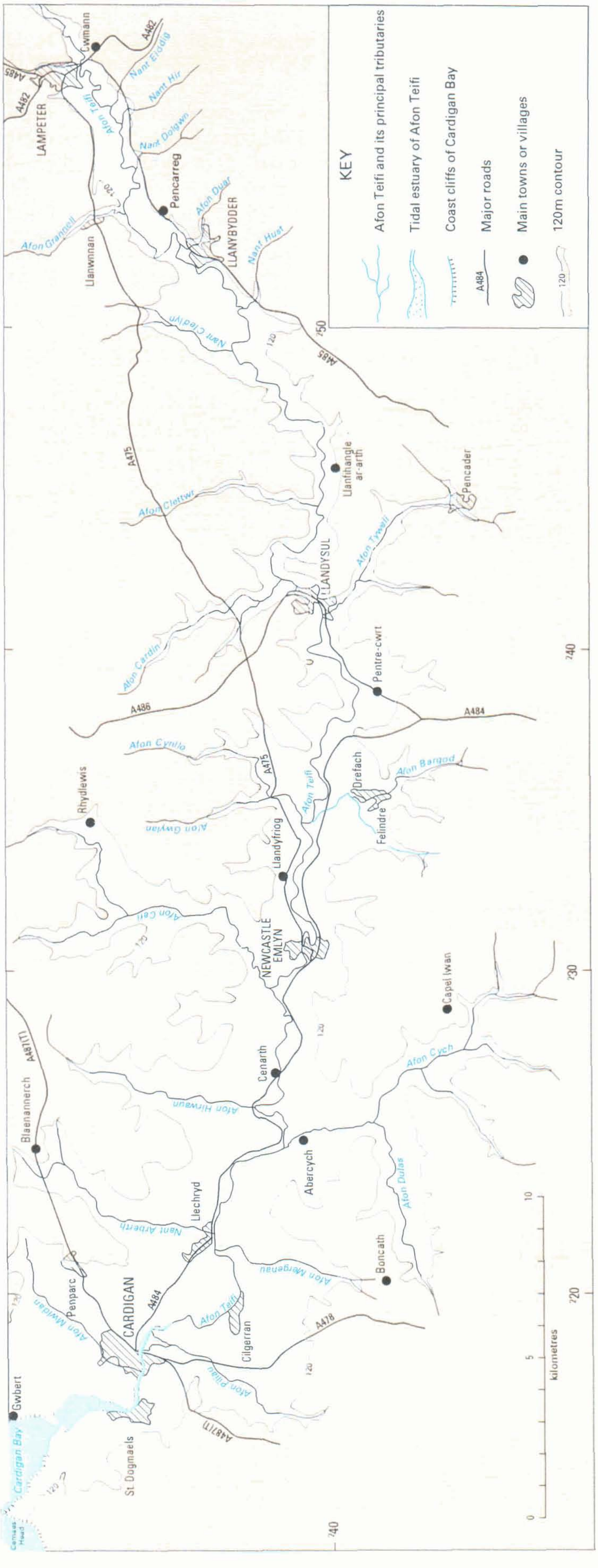

Figure 1 Map of the project area.

provided, and where the limitations of the information portrayed are more fully assessed. Though the report and its thematic maps are intended to provide stand-alone information for use in land use planning and development, they should also be seen as components of a more detailed and extensive BGS database, which should be consulted in the course of site specific investigations. This database includes all the primary material from which the report and maps are derived, including geologist's field slips, locality descriptions, borehole, trial pit and geotechnical data, borehole core, rock samples and geophysical information. These data are held in the NGRC, at BGS Keyworth and, with the exception of material donated on a confidential basis, are available for inspection by prior arrangement. Primary hydrogeological data are held at BGS Wallingford.

The co-operation of all those who supplied data is gratefully acknowledged.

All National Grid References in the report lie within the SN 100 km square. Grid references are either given eight figures (accurate to within 10 m) for specific sites, or six figures (accurate to within 100 m) for general locations.

The report presents the views of the authors, which may not necessarily be those of the cofunding local authorities or the Environment Agency (Wales).

Orders for copies of this report or enquiries concerning it, should be directed either to:

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2 Geological and Geomorphological background

Geologically, the catchment comprises solid rocks of Ordovician and Silurian age with a discontinuous, but locally thick cover of superficial deposits (drift) of Quaternary age (see Thematic Maps 1 and 2). The solid rocks are exclusively sedimentary and predominantly comprise mudstones, siltstones and sandstones. The drift deposits include glacial materials, mainly mixtures of clay, silt, sand and gravel, left after the last Ice Age, as well as materials which have accumulated subsequently (and are still accumulating), principally river sediments, head, beach deposits and blown sand. The solid rocks were deposited between 450 to 420 million years ago. The oldest exposed drift deposits however, are probably no greater than 122 000 years old, although older drift materials may be preserved at depth within the buried portions of the Teifi valley system. Although the interval between the formation of the solid rocks and the deposition of the drift spans a considerable period of time, the main landscape features of mid Wales, including those of the Teifi valley formed during the late Tertiary and early Quaternary periods (between 1 and 24 million years ago). These landscape features were modified during the glaciation of the region, and influenced the distribution and geometry of the Quaternary deposits of the catchment (Figure 2). The geological and geomorphological features of the project area, therefore, are related to three separate episodes: 1) the formation of the solid rocks; 2) the development of the pre-glacial landscape; and 3) glaciation and formation of the modern landscape. The principal geological events to affect the region are summarised in Figure 3.

2.1 FORMATION OF THE SOLID ROCKS

There has hitherto been little systematic examination of the Ordovician and Silurian rocks of the catchment. The limited history of work by the Geological Survey has been discussed above. An early study of the rocks around Cardigan was undertaken by Keeping (1882a). More recently, James (1975) has described the cliff sections at Poppit Sands, Anketell (1987) and his students, Tata (1985) and Kishimoto (1989), have studied areas in the centre of the catchment, whilst Craig (1985, 1987) and McCann (1990, 1992) have studied the coastal sections. Orr (1995) has provided details of fossil traces in strata near Lampeter. Important regional studies, which have a bearing on the solid geology of the catchment, are provided by Jones (1938, 1956), Bassett (1969), Cave and Hains (1986) and Davies et al. (1997).

The rocks of the region were deposited in a marine sedimentary basin, the Welsh Lower Palaeozoic Basin, which occupied much of western and northern Wales some 400 to 500 million years ago. The mudstones, siltstones and sandstones display features which are consistent with deposition under water which was certainly several hundred metres in depth, and more likely greater than a kilometre. Many of the rocks occur as parallel-sided beds. The bases of these beds are sharp (i.e. not gradational). Where sandstones and siltstones are present, they typically exhibit evidence of scour into the underlying material. Sandstone beds are commonly coarsest near their bases; they may fine upwards into siltstones and these into mudstones; siltstones invariably pass upwards into mudstones. Fossil shells are absent, but tube-like fossils called graptolites are abundant. They represent the skeletal material of extinct organisms, which once floated in the sea. These observations allow certain conclusions to be drawn about how the rocks were deposited. They indicate that many of the mudstones, siltstones and sandstones were laid down by fast moving, but short-lived marine currents, which carried sediment (sand, silt and mud) from the edges of the basin across the basin floor. In modern oceans, these cloud-like sediment flows are termed turbidity currents and the parallel-sided beds they deposit are known as turbidites. Turbidites make-up over ninety percent of the rock succession of the catchment. Chaotic or poorly bedded (slumped) material, formed by underwater landslips along the basin margin slopes, is also present. Thin beds of black, laminated pyritic mudstone or grey, mottled mudstone occur between each turbidite deposit. They represent the mud brought into the ocean by rivers and storms to slowly settle out on to the basin floor. The dark mottling is due to worm-like organisms burrowing for food in the mud. The dark laminated mudstones formed during periods when stagnant sea conditions prevented the activity of these burrowers.

When the solid rocks were deposited as unconsolidated sediments, the configuration of the British Isles was very different to today. Wales lay on the south side of the equator, close to the northern margin of a very small continent with an ocean to the north. The forces of continental drift (plate tectonics) moved this continental slice northwards towards a much larger continental mass, which included the rocks that now form northern Scotland. The two continents collided during the late Silurian to mid Devonian period, in a geological event known as the Caledonian Orogeny (Figure 3). High mountains, perhaps comparable to the present day Alps, were created in areas of the Lake District and Scotland, which were situated much closer to the point of collision. As the sediments within the Welsh Basin were squeezed, they buckled and fractured, a cleavage was developed, and they were uplifted to form dry land (Davies et al., 1997). It is the pervasive effects of this orogeny, observed as wave-like contortions of the bedding (folds) and dislocations with quartz veins (faults), which are often the most eye-catching features of sections in the rocks of the catchment (Plates 12 and 13).

2.2 DEVELOPMENT OF THE PRE-GLACIAL LANDSCAPE

Any rocks which formed during the interval between these ancient upheavals and the onset of the glacial epoch are no longer preserved in the Teifi valley, or indeed across much of western Wales. However, some insight into the events which took place during this prolonged period can be

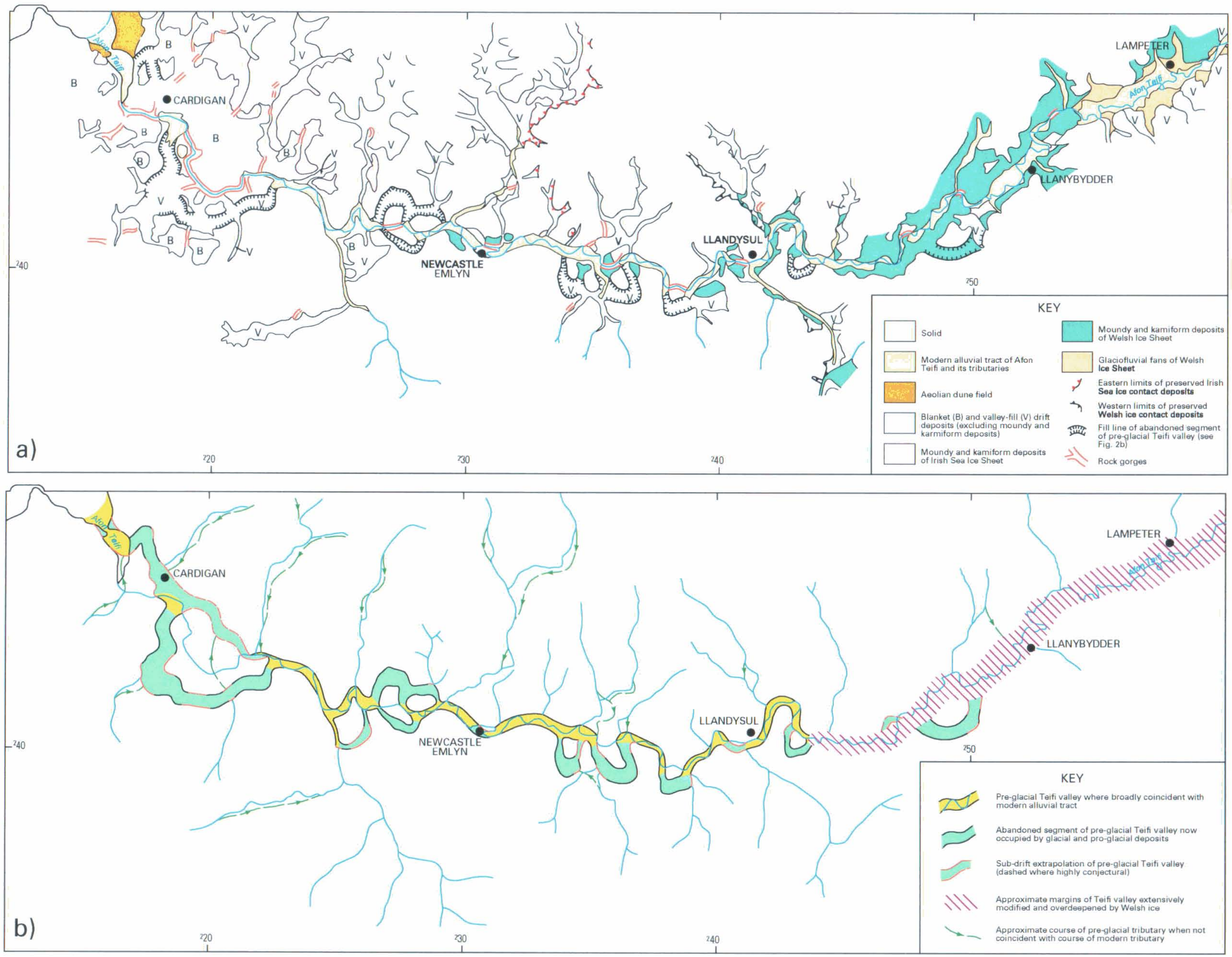


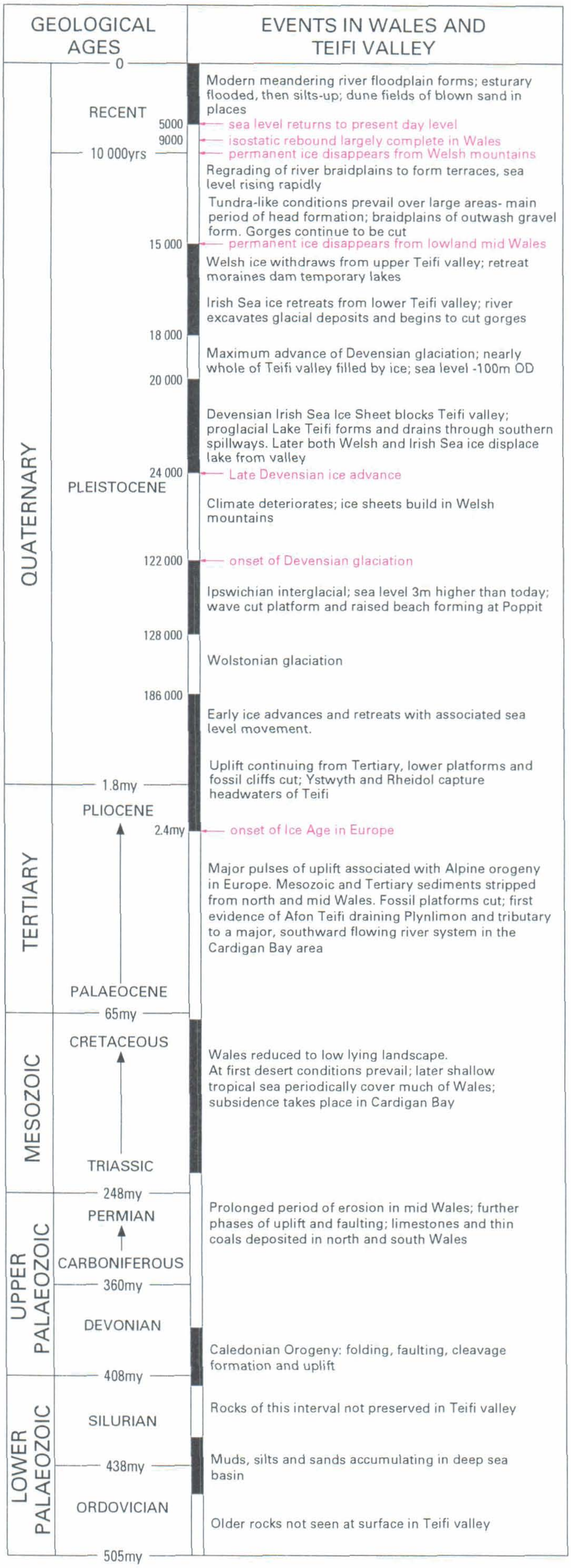
Figure 2 Main geomorphological features, a) drift deposits b) modern and abandoned courses of the Afon Teifi.

determined from the form of the Welsh landscape, and the rocks in adjacent regions (Figure 3). The history of this period has been reviewed by Jones (1951, 1956), Brown (1960) and George (1974). Recent work offshore, assessing the complex geology of Cardigan Bay, has added further insights to this problem (e.g. Dobson and Whittington, 1987; Tappin et al., 1994).

Throughout the early part of this period, western Wales probably formed an upland region, perhaps similar to today, although under very different climatic regimes, which changed progressively as plate tectonic forces continued to move the continental mass northwards. However, by Mesozoic times, erosion had substantially reduced the relief of this former landscape, and pulses of subsidence are believed to have allowed a tropical sea to periodically re-invade the heartlands of Wales, and to deposit sediments. During this period, a shift in plate tectonic forces initiated the Atlantic Ocean. Europe cleaved from North America and began to move northeastwards; this process continues today, and has brought Wales to its present latitude and longitude (Cope et al., 1992). Near the end of the Mesozic, over 65 million years ago, these major tectonic events initiated a period of massive uplift in Wales, which continued throughout the Tertiary era. This saw the beginning of a protracted period of denudation, still ongoing today, during which remnant Mesozoic sediments were eroded from mid Wales. Uplift and erosion was not a single continuous event, but took place in stages, now recorded by fossil rock platforms and cliff lines, still discernable at a variety of elevations today (Brown, 1960). The final phases of uplift, if indeed it is complete, occurred early in the Quaternary, some 2.4 to 0.6 million years ago; only then did the mountains of north and mid Wales first attain their present elevations; although cored by ancient rocks, they are, geologically, very young (Figure 3).

The Teifi valley had its origins during this period of massive erosion. By mid-Tertiary times there is evidence of a major river system draining the floor of what is now Cardigan Bay, with tributaries, including the Afon Teifi, extending eastwards into the newly formed Welsh uplands (Dobson and Whittington, 1987). Later, near the end of the Tertiary, the so-called 600-foot platform was being cut by waves, which broke on a coastal cliff line situated at a level broadly equivalent to the 200 m contour of the modern landscape. The map of this fossil coastline reveals an already broad Teifi valley, probably occupied by a meandering river, which joined the sea at a point above where Cenarth is situated today (Brown, 1960). This proto-Afon Teifi had its headwaters on the southern flank of a newly fashioned Plynlimon (Jones, 1946; Jones and Pugh, 1935; Coster and Gerard, 1947).

Subsequently, sea level fell in stages, represented in coastal regions of Wales by the 400-foot, 300 foot and 200-foot platforms, until it lay at a level close to that of today. In response, the Teifi cut downwards into its earlier valley floor to establish the broad form of the modern valley. However, the picture is more complicated than this, for the river did not maintain



my = million years BP (Before Present)

Figure 3 Main geological events to affect the Teifi catchment.

and incise a single course. Jones (1965) has identified deeply-incised, pre-glacial courses of the river which record two or more periods of downcutting in rock, each followed by sediment infill and river diversion. In places, the modern river follows these pre-glacial valleys, but elsewhere it pursues a more recent course, leaving these earlier routes abandoned and locally concealed (Figures 2 and 4a). These pre-glacial courses of the Teifi have been studied by geophysical methods previously by Allen (1960), Francis (1964) and Nunn and Boztas (1977), but in far greater detail during this project (Carruthers et al., 1997; see Appendix 2). The thick drift sequences which infill these former valley segments have now also been proved by drilling (see Appendix 3). These studies demonstrate that the ancient courses of the Teifi extend near Cardigan to depths of up to -40 m OD. Offshore, the floor of the valley is known to descend to -60 m OD (Lear, 1986). It is clear that periodically, sea level fell to much lower levels than the platforms suggest, and much lower than it is today. The inference is that the Ice Age was already in progress, and that these periods of deep incision into rock relate to the substantial falls in sea level which accompanied the early advances of polar and continental ice. The platforms mark the levels to which the sea returned during periods of ice retreat, each level (400-foot, 300-foot and 200-foot) being lower than the one before. These were times when the valley silted up with fluvial sediment, raising the floor of the river to the appropriate platform level. The course followed by the river when it next cut downwards was locally different from that of the previous period of downcutting, and so the different generations of rock valleys were carved. Whether ice ever invaded the valley during this late Tertiary/early Quaternary period is unknown, for no deposits dating from this interval are preserved. At some stage during this period, both the Afon Rheidol and Afon Ystwyth, experiencing their own episodes of rapid downcutting, captured the northern headwaters of the proto-Teifi. The large river which had cut the broad lower reaches of the Teifi valley was thus much reduced in size and that which remains, sourced from Llyn Teifi, is a misfit river.

2.3 GLACIATION AND FORMATION OF THE MODERN LANDSCAPE

2.3.1 History of Quaternary research

In contrast to the solid rocks of the catchment, the drift deposits of the area, and the glacial deposits in particular, have been the focus of much scientific work (reviewed by Campbell and Bowen, 1989). Early studies of the glacial deposits of the region include those by Keeping (1882b), Jehu (1904) and Williams (1927), who sought to establish the drift stratigraphy of the area. Charlesworth (1929) was the first to propose that a large glacial lake, Lake Teifi, once occupied the valley during the last ice age. These studies demonstrated that the region was affected by two separate ice masses, the deposits of which are preserved in the area. The Welsh Ice Sheet descended westwards from the Cambrian Mountains, while the Irish Sea Ice Sheet, sourced from much further north, spread southwards to occupy much of Cardigan Bay and its coastal tract. The maximum extent of both ice sheets and the timing and products of their advances in west Wales has been much debated (Griffiths, 1940; Wirtz, 1953; Mitchell, 1960, 1962, 1972; Synge, 1963; Watson, 1970; Potts, 1968, 1971; Bowen 1974; Tappin et al., 1994).

In detail, the Ice Age included several discrete periods of ice advance, each accompanied by a fall in global sea level. These were separated by intervals during which the climate improved, the ice retreated, and sea level rose. It is generally accepted that the most extensive ice advances occurred between 900 000 and 130 000 years ago (Funnell, 1995); and include events known in Britain as the Beestonian, Anglian and Wolstonian glaciations. During at least some of these advances, the whole of Wales is thought to have been covered by ice (Campbell and Bowen, 1989). Some authors, notably Watson (1970), have argued that these early glaciations were the only ones to have affected south-western Wales. A more widely held view is that the deposits of the Wolstonian and earlier advances (the so-called Older Drift) were largely destroyed or reworked during the subsequent, more recent, Devensian glaciation. This began around 115 000 years ago, but reached its climax just 20 000 years ago, during the Late Devensian (Figure 3). Although this advance was less extensive than earlier ones, it is principally the materials left following the final retreat of the Devensian Irish Sea and Welsh ice sheets (the so called Newer Drift), around 15 000 years ago, which dominate the modern landscape of the Teifi catchment. The warmer period which preceded the Devensian glacial episode is known as the Ipswichian Interglacial. Rock benches observed along the cliffs on either side of the Teifi estuary, at Poppit and Gwbert, are thought to represent fossil wave-cut platforms, formed during this period (John, 1971; Bowen, 1977; Campbell and Bowen, 1989), when sea level was evidently higher than it is today. Cross-bedded, iron-impregnated sands, which rest on the fossil wave-cut platform at Poppit have been interpreted as associated beach deposits. They contain rare foraminifera which support an Ipswichian age (Lear, 1986).

In a major study of the Teifi valley, Jones (1965) proposed that Charlesworth's Lake Teifi was created as retreating Devensian Irish Sea ice blocked the valley and impounded the glacial meltwater. During the retreat, the lake waters escaped southwards via cols in the watershed, cutting deep spillways in rock. Subsequently, as the ice melted and withdrew from the area, Lake Teifi drained and the river excavated its modern course, cutting rock gorges as it did so (Figure 2) (see front cover). As support for their glacial model, both Charlesworth and Jones cited exposures of laminated (varved) clays within the Teifi valley as deposits typical of glacial lakes.

Other authors have sought to modify this model. Bowen and Gregory (1965) suggested that the gorges and spillover channels of the region were formed sub-glacially. Support for this idea has been offered by John (1970) and in subsequent papers by Bowen and others (Bowen, 1967, 1971; Bowen and Lear, 1982). Lear (1986) went further, arguing that the older valleys recognised by Jones (1965) were fashioned by pre-Devensian Welsh ice as it moved down the valley. He recognised a sub-drift rock sill across the mouth of the estuary, similar to features seen in modern fjords. According to Lear, the rock gorges were cut by glacial streams, associated with this older ice advance. Although they were subsequently plugged by Devensian Irish Sea till, the modern river simply re-exhumed the gorges once the ice had retreated. Despite these re-evaluations, all workers appeared to agree that a late Devensian, meltwater lake briefly occupied the valley.

Jones (1965), rejecting earlier interpretations (e.g. Charlesworth, 1929; Mitchell, 1972), regarded the conspicuous sand and gravel mounds at Banc-y-Warren [2045 4749] (Plate 7) as the remains of a delta, which built out into Lake Teifi, and was supplied by Irish Sea ice meltwater, Organic remains have been used to date the deposit as between 30 000 and 40 000 years old (Brown et al., 1967; John, 1967; John and Ellis-Gruffydd, 1970), although the validity of the techniques used and the dates obtained are seriously questioned (Shotton, 1967; Boulton, 1968). In contrast, different dating methods used by Bowen (1984) support a Late Devensian age, around 18 000 years ago. Detailed sedimentological investigations of these deposits include those by Helm and Roberts (1975) and Allen (1982). Helm and Roberts also considered the deposit to be the remnant of a delta formed at the margin of Lake Teifi. In contrast, Allen suggested that it was laid down by streams flowing on top of an ice sheet and was subsequently let down as the ice melted. Worsley (1984) has endorsed this view.

In a radical reappraisal of Banc-y-Warren, and the glacial succession of the Irish Sea region in general, Eyles and McCabe (1989) interpreted the glacial sequences of the western Teifi valley as glaciomarine in origin. Although the general validity of their model is doubted (Wingfield, 1992), Eyles and McCabe argued that the weight of the Irish Sea Ice Sheet caused the land beneath it to subside, allowing the sea to invade the coastal tract of Cardigan Bay as the ice began to retreat. They, therefore, interpreted the Banc-y-Warren deposits as the remnants of a delta which built out into the sea rather than a lake. After the ice had completely melted, the land reverted to its original level, a process known as isostatic rebound. In mid Wales, the rebound from Devensian ice loading is thought to have largely been completed around 9 000 years ago, so Devensian deposits older than that, as at Banc-y-Warren, actually formed at a lower altitude than they occur today.

The remnants of supposed Welsh meltwater-fed deltas, which built out into Lake Teifi, have been recognised at Pentre-cwrt [395 394] (Jones, 1965), near Llanllwni [480 410] (Price, 1977), at Llanwnen [523 472], Llanybydder and Pencarreg [530 455] (Parry, reported in Lear, 1986), and at Lampeter (Watson, 1965).

2.3.2 Results of present survey

With the exception of Price (1977) and Lear (1986), earlier investigations of the Teifi valley did not produce detailed regional maps of the distribution and relationships of the various drift deposits. The present study, in providing such maps, offers an opportunity to reassess the existing glacial and post-glacial models for the area and to build on the ideas arising out of the BGS investigations at St Dogmaels (Fletcher, 1994, 1996; Fletcher and Siddle, in press). Glacial lake deposits are now recognised as widespread throughout the western reaches of the catchment, with thick sequences preserved within the abandoned, pre-glacial segments of the river system, as well as below the modern alluvium. They are present at elevations ranging up to 130 m OD. These extensive glaciolacustrine sequences do not appear to overlie earlier tills, or to display glaciomarine characteristics, and therefore do not support the models of Lear (1986) and Eyles and McCabe (1989). However, the distribution of these sediments is consistent with: i) deposition within a single, very large and relatively long-lived, ice-damned lake, consequent to the blockade of the Teifi estuary by Devensian Irish Sea ice; ii) the progressive rise in the level of this lake as the ice sheet spread inland; and iii) the development of a succession of southern spillways at Cippin, Llantood and Pedran (Figure 4b). The new model differs from that of earlier authors in recognising Lake Teifi as an early Late Devensian feature. Irish Sea till resting on the glacial lake clays demonstrate that the Irish Sea ice sheet overrode these clays and displaced the lake from a large portion of the catchment (Figure 4c). Whether the lake reformed as the ice retreated is unclear. It is possible that this was a time when wasting masses of ice ponded a series of smaller, temporary lakes (Figure 4d). Subsequently, as the last of the Irish Sea ice disappeared, the Afon Teifi returned and began to cut into the newly deposited, commonly unstable, glacial materials which then filled its valley. Many of the landslips in the region were initiated at this time. This was a period of massive erosion, when huge volumes of glacial deposits were flushed out of the catchment as the river and its tributaries, engorged by meltwaters, sought to establish their modern courses. This process was given impetus by a sea level which, though rising, was still much lower than today. The effects of isostatic rebound must also have been important. At intervals along its length, the river soon cut through these new sediments to flow on bedrock and eventually cut the gorges (Figures 2 and 4d) (Plate 1 and front cover), which are a major feature of the river today. In so doing, it abandoned extensive segments of its pre-glacial valley, leaving some of these partially excavated, but others still buried beneath Devensian deposits. Viewed in this way, the cutting of the gorges can be seen as merely the most recent in the succession of river diversions and incisions which had their origins during the Tertiary (see above).

The new mapping, building on an earlier study by Price (1977), also offers insights into the movement and effect of Welsh Devensian ice in the eastern reaches of the catchment. Its initial advance into the area was probably in the form of a valley glacier confined within the main Teifi valley. Scour at the base of this glacier is reflected in 'U'-shaped valley profiles to the east of Llandysul. Lake Teifi clays extend as far east as Maesycrugiau [474 413]. Welsh tills and ice-contact glaciofluvial sands and gravels extend as far west as Croes-lan [386 460], in the north, and Pencader [455 360], in the south (Figure 2). It is clear that westward moving Welsh ice overrode and displaced Lake Teifi from eastern parts of the valley, just as the Irish Sea ice had done in the west. At its western edge, the Welsh ice supplied meltwater streams which carried sediment into surviving parts of the lake, building deltas of silt, sand and gravel, now recognised as the undifferentiated glaciofluvial deposits at Llandysul, Pentre-cwrt [395 394]and west of Henllan [355 403], as described by Jones (1965) (Figure 4b). There is no evidence to suggest that Lake Teifi ever returned to parts of the valley east of these deposits. It is inferred that Irish Sea ice degraded and contracted more quickly than the land based Welsh ice sheet due to its maritime setting (Campbell and Bowen, 1989). The barrier, or barriers, it formed were breached before there was significant eastward withdrawal of Welsh ice, allowing lake waters to drain and a fluvial regime to be re-established in the western reaches of the catchment.

Tills preserved outside the main river valley confirm that, at the time of its maximum advance, Welsh Devensian ice had spread as a sheet across the higher ground to the north and south (Figure 4c). As this ice began to melt, it retreated first from these interfluves and survived the longest in the valleys where it was thickest. Glacial debris accumulated along the margins of this wasting valley ice to form the extensive lateral benches of ice contact deposits (kames), which are a feature of the valley up-river from Llanfihangel-ar-arth [450 400]. Locally, at points where it

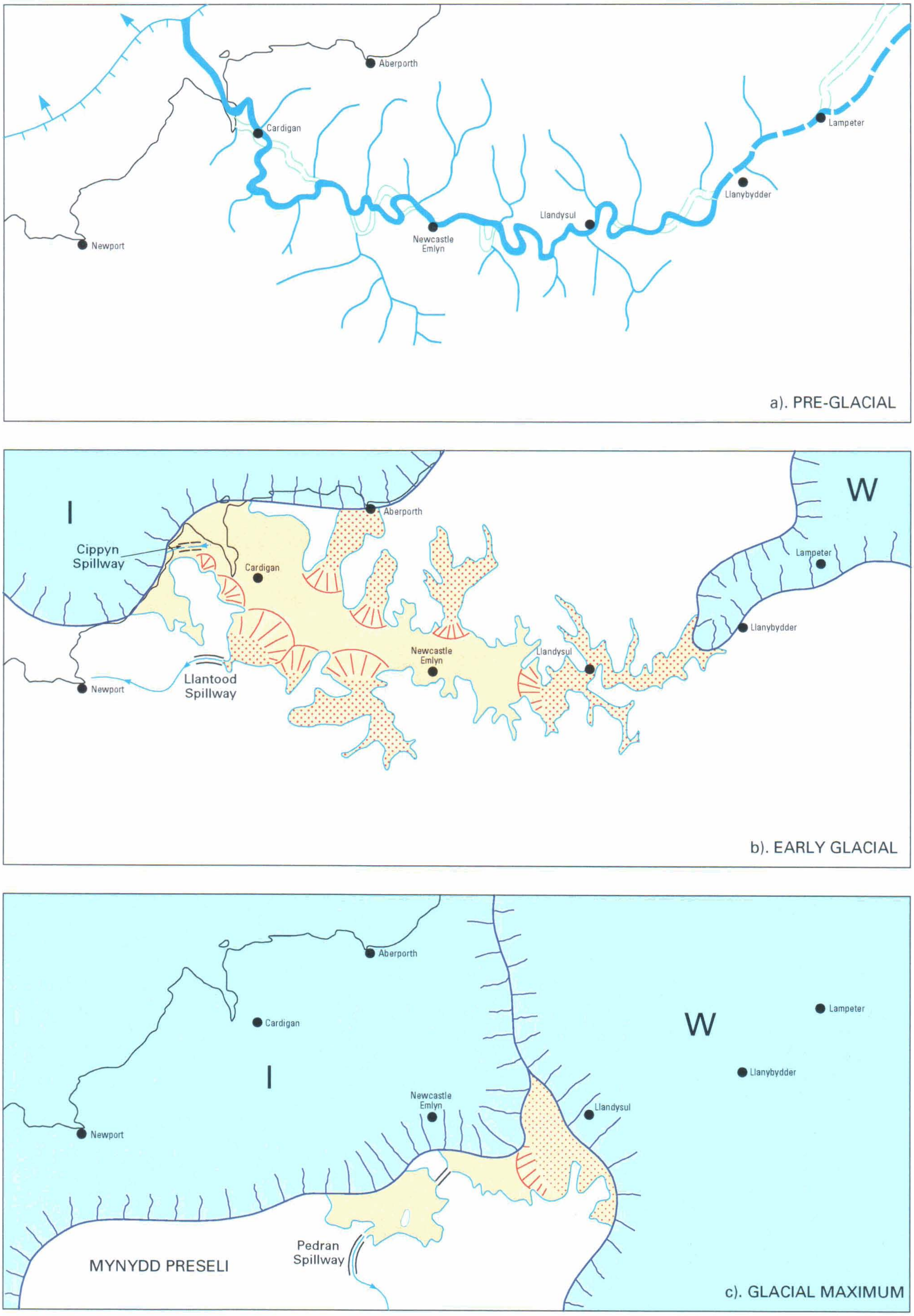


Figure 4 Early to Late Devensian glacial history of the Teifi catchment; a), b) and c); for d) and e) see facing page.

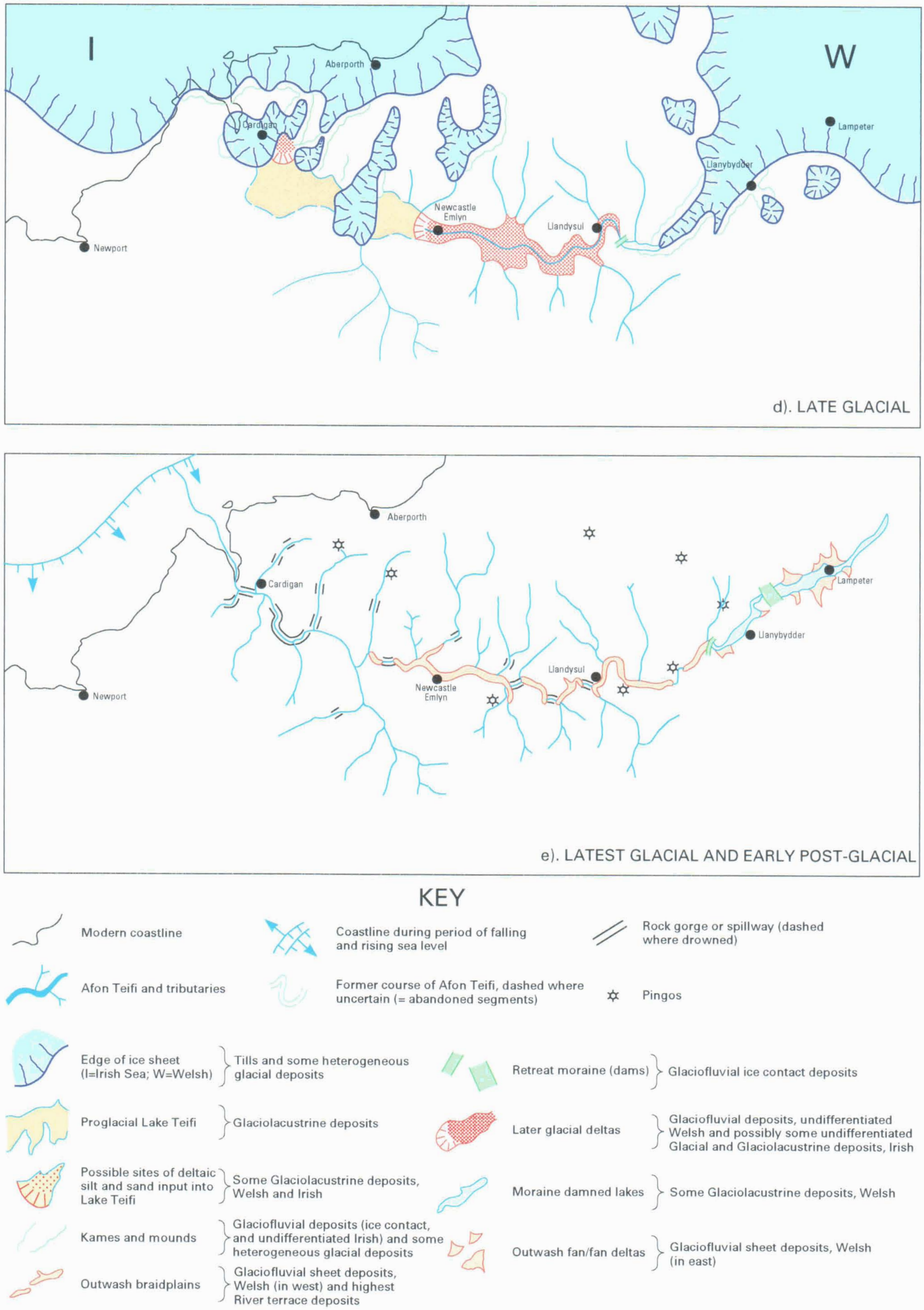


Figure 4 *Continued*

paused during its retreat, similar debris accumulated at the front of the remnant ice. As the eastward withdrawal of the ice resumed, this frontal material was left as mounds and ridges, which blocked the valley (retreat moraines). These structures served as temporary dams, impounding glacial meltwaters to create a succession of eastern lakes (Figure 4d and e). Eventually, as the level in each lake rose, its waters spilled over and cut through its morainic barrier, allowing the lake to drain and establishing the course which the river follows today. At Maesycrugiau [474 413], Rhuddlan [495 430] and Pencarreg [530 460], these lake spillwaters cut through thin morainic barrier deposits at the sides of the valley and, having determined their course, continued to cut down into rock. Near Llandysul and Glanrhydypysgod [468 402], escape channels were cut in morainic barrier deposits or excavated the former side of the valley. Outwash from tributary valleys spread into these lakes, or on to the drained lake flats, as alluvial fans and fan deltas (Figure 4e). These features are still recognisable today in the form of the glaciofluvial sheet deposits between Rhuddlan and Lampeter (Figure 2). Abundant kettle holes, now partially filled by lacustrine alluvium, show that masses of stagnant ice were still present in some parts of the valley as these outwash fans advanced.

With the disappearance of glacier ice from the region, tundra-like conditions prevailed and gave rise to a spectrum of distinctive frost-related structures and landforms, including pingos, which have been described by Watson (1965) and Watson and Watson (1974) (Figure 4e). Heave, shattering and solifluction promoted head formation, and it is probably during this period that most of the surface head deposits accumulated. At this time, the modern alluvial tract of the Afon Teifi also began to evolve (cf. Macklin and Lewin, 1986). Erosion in the west (see above) gradually gave way to deposition throughout the catchment. Initially, a braided, gravel and sand dominated river system was established in response to high seasonal discharges and massive sediment output from melting ice. Regrading of the river during this period established braidplains at successively lower levels, with remnants of earlier levels preserved as high terraces. Later, as the discharge of water and sediment gradually diminished, the modern meandering river system evolved at an even lower level, creating the modern floodplain and promoting alluvial deposition of overbank silts and muds as well as channel sands and gravels. Deepening of the rock gorges continued throughout this period and is still ongoing today.

Plate 1 Cilgerran Castle, Afon Teifi and the Cilgerran Gorge [1982 4296].

The present-day sea level was established around 5000 years ago and, at this time, the lower Teifi valley was drowned, possibly as far as the Cilgerran gorge [1950 4300]. The estuary has subsequently silted up with tidal river and salt marsh deposits, and a sandy spit of shoreface and beach deposits (Plate 3), has grown across the river mouth. West of the present coastline, dune fields of blown sand were developed on glacial sediments, newly exposed along the sides of Cardigan Bay as the ice retreated. As sea level rose, they migrated landward to their present sites, the larger dune complex developing on the north side of the estuary (Towyn Warren), where there was optimum exposure to the prevailing westerly winds.

3 Drift deposits — Thematic Map 1

This thematic map shows the surface distribution of superficial materials which rest on solid rock including both artificial (man-made) deposits and natural drift deposits. It also shows areas where there has been extensive excavation of the natural ground surface (worked ground); as well as the sites of large areas of landslip. One or more drift deposits may intervene between the surface deposit (natural or artificial) and solid rock, and some of the likely patterns of superposition within different sectors of the catchment are indicated on the schematic sections on Map 1.

3.1 ARTIFICIAL DEPOSITS AND WORKED GROUND

Worked ground

Areas where the natural ground surface has been cut away by man in the pursuit of mineral resources, and which have not been back-filled, are depicted as worked ground. The largest areas of worked ground relate to sites of sand and gravel extraction notably to the west of Penparc, where the active Cardiganshire Sand and Gravel Pit [2020 4847] currently extends to over 8 hectares. Defunct, but extant sand and gravel pits [2111 4355] and [2121 4370] also occur in the Llechryd area. The location of excavations too small to be depicted at 1:50 000 scale, including many quarries in rock for building stone or aggregate, are shown on Thematic Map 3.

Made ground

Areas where the present ground surface is known to be underlain by material, which has been deposited by man and is generally in excess of a metre in thickness, is described as made ground. This can include areas where pre-existing pits, quarries and other forms of excavation have been partially or wholly back-filled, as well as areas where the deposition of materials has been used to elevate the ground surface as, for example, with railway and road embankments and for flood prevention. Made ground may be composed of essentially natural materials which have been excavated from one site and deposited at another, as with adjacent road cuttings and embankments, or it may include varying proportions of man-made waste materials. Natural materials include many of the drift deposits described below, as well as excavated rock. Man-made materials can include both toxic and inert waste of either domestic or industrial origin. Moreover, the composition of an area of made ground may vary greatly, especially if different types and proportions of material were used during its construction. The location of areas of made ground too small to be depicted on Thematic Map 4 are shown on the 1:25 000 scale geology maps.

As would be expected, areas of made ground are most common in and around the main towns and villages, reflecting the higher levels of human activity in such areas. Spoil from farm quarries and cuttings in rock represent the most common form of made ground in rural areas. Some of the largest areas of made ground, volumetrically, are linear embankments, which occur at intervals along the main roads within the catchment, and along the disused Aberystwyth-Carmarthen railway, notably between Pencarreg and Lampeter. Embankments along the disused Cardigan-Carmarthen Railway, for example at Rosehill Marsh [186 455] near Cardigan, include a high proportion of slag brought from steel works in South Wales. The boulder-faced coastal defences [1606 4870] at Gwbert are also depicted as made ground.

Landscaped ground

Areas where the original ground surface has been extensively remodelled, so that it is impossible or impracticable to distinguish areas of cut, from areas of fill (made ground) are distinguished as landscaped ground. Much of the ground within any town, or along any major road or railway has undergone a degree of remodelling, but the level of disturbance is generally superficial and insignificant in terms of effecting overall ground form or conditions. Here, landscaped ground is restricted to areas where major restructuring of the land surface has occurred, such that the original form of the ground is no longer readily discernable. Areas depicted as landscaped ground may occlude the sites of pre-existing excavation that may or may not have been back-filled prior to landscaping. For example, the King George's Field [183 467] in Cardigan includes the site of former clay workings. The largest areas of landscaped ground are the modern industrial estates in Cardigan and Lampeter. Smaller areas include sites at Pencader [4461 3620] and the numerous pre-historic forts and encampments. The fill material included within areas of landscaped ground is likely to be composed of the material derived from areas of excavation within the site.

Disturbed ground

Disturbed ground is used for areas of ill-defined surface mineral workings, where areas of excavation are complexly associated with areas of fill and spoil (made ground). In the catchment it has been used to for two sites [3114 4242] and [3396 3999] of glaciolacustrine clay workings near Newcastle Emlyn and Pentrecagal respectively.

3.2 NATURAL DRIFT DEPOSITS

A total of 26 different categories of natural drift deposit have been recognised in the catchment. They have been divided into two principal groups: i) post-glacial deposits, including landslips. ii) deposits of the last glacial period. In addition to their geological origin and relative age, this division also reflects important differences in the composition, mechanical properties and distribution of the two groups of deposits. A further, pre-glacial category of drift deposit, older alluvium, is shown on the schematic sections of Map 1, but does not occur at the surface.

The following section provides a description of the materials present in each category of drift deposit, together with an assessment of their mode of deposition. An understanding of the processes and environments under which each drift deposit formed underpins predictions concerning their gross geometry, thickness variability and internal consistency. Such factors have an important bearing on the mineral resource potential and/or engineering ground conditions of many of the deposits.

3.2.1 Post-glacial deposits

Landslips

Landslips in the catchment comprise masses of material which have undergone downslope movement due to slope failure. Only the largest landslips are shown on Map 1. The locations of all landslips recognised during the course of the survey are shown on Thematic Map 6 and their nature and distribution is assessed in detail in the part of the report describing that map.

Head

Small patches of head (excluding head gravel) occur widely scattered throughout the catchment, principally derived from the glacial deposits of the region. They comprise highly variable, but typically sandy and silty clays with variable proportions of gravel grade clasts; where larger clasts are abundant they may exhibit alignment or imbrication. Head deposits represent pre-existing, unconsolidated material that has suffered down slope movement by solifluction, slope-wash or mud-flow processes to be redeposited in gullies and depressions. Most head accumulated during the late glacial and early post-glacial periods. In accord with its origin, the matrix and clast composition of individual head deposits will closely reflect the character of the adjacent source materials. Clay-rich tills, heterogeneous glacial deposits and gaciolacustrine deposits give rise to head clays with scattered pebble, cobble and boulder grade clasts. Glaciofluvial sand and gravel deposits give rise to head composed of variably pebbly sands and silts. Such head is commonly associated with sites of groundwater seepage, in which case it becomes a highly compressible, water saturated deposit, locally rich in organic debris (peaty head) and prone to further downslope flowage. Where it has escaped the influence of modern agriculture and drainage, such head supports a distinctive flora of reeds and rushes, well seen at the botanical SSSI [1978 4858] north of Glanllynan.

Head deposits generally thicken towards the centre of the former gulley or depression they infill; only exceptionally are they likely to exceed 5 m in thickness.

Head gravel

This more widespread type of head comprises clast supported, commonly bedded and moderately well sorted, clayey and silty gravels typically composed of angular mudstone fragments (Plate 2). A silty clay matrix typically coats and binds the rock fragments, but seldom occludes the voids between the clasts completely. The mudstone clasts, dominantly of coarse sand to pebble grade, can vary from fresh to deeply weathered. Head gravels flank areas of solid outcrop and occur extensively within the confines of the tributary valleys of the catchment. They represent downslope scree-like accumulations of frost-shattered rock debris and rock weathering products generated principally under the tundra-like conditions, which prevailed during the late glacial and early post-glacial period. Fining-upwards sequences and intercalated clay seams record variations in the rates of clast production and of debris accumulation and reflect the climatic oscillations of that time. With the establishment of the current temperate climatic regime, the formation of head gravel has largely ceased and the deposits are now generally vegetated and stable. Compared with the ordinary (clay-rich) head, head gravels give rise to better drained, generally steeper slopes which may be at or close to the original angle of repose of the material.

Plate 2 Stratified head gravel, composed of angular mudstone fragments, roadside cutting [2218 4388], Llechryd.

Good sections in cross-bedded head gravels with fining-upwards sequences and thin red clay seams are provided by cuttings [2218 4388] in Llechryd, where up to 5 m are exposed (Plate 2). Where head gravels flank solid rock, they will generally display a wedge-shape geometry thinning away from a steep and possibly irregular contact with the rock. The geometry of head gravels which floor the bottoms of tributary valleys will reflect the original form of the valley in rock. In some of the wider valleys, the head gravels may be tens of metres thick.

Blown sand

Blown sand is the result of beach sand being carried inland by the wind to be deposited as dunes of well sorted, fine-grained, unconsolidated (running) sand. Such dune fields occur on both the northern and southern sides of the Teifi estuary. The larger, northern field, known as Towyn Warren, extends over 1.5 km^2 within the area surveyed. The southern field covers around 0.3 km^2. In both areas only the seaward dunes are currently active; inland the dunes are largely degraded and heavily vegetated. Sections in the sands reveal levels rich in terrestrial gastropod shells and layers rich in carbonaceous material and rootlets testifying to earlier periods of colonisation by vegetation.

Typical sections in blown sand are provided by the low cliff [1615 4855] to the south of the caravan park at Gwbert. The thickness of blown sand is likely to vary in accord with the topographic variation of the dune forms. Beneath dune peaks, the deposit may range, exceptionally, up to 10 m in thickness, thinning markedly beneath the intervening the troughs. Locally, on Towyn Warren, underlying drift deposits and solid rock are known to crop out in the troughs between dune peaks.

Peat

Peat comprises accumulations of partially decayed, and highly compressible, dark brown vegetable matter formed under water-logged conditions. Small areas of peat have only been mapped in the vicinity of Waungilwen [3472 3943] and Pencarreg [5334 4523], and here the deposits include variable amounts of silt and clay and are gradational with organic-rich lacustrine clay deposits. The thickness of these deposits is unknown, though a metre was penetrated by auger.

Alluvium

The highly variable suite of river deposits including clays, silts, sands and gravels which directly underlie the present floodplains of the Afon Teifi and its larger tributaries are collectively termed alluvium. Cross-bedded, pebble cobble gravels and coarse to fine-grained sands represent former river channel deposits and probably occur as steep-sided, tabular bodies 2 to 3 m deep and tens of metres across. Though typically unconsolidated, these gravels and sands locally display layers strongly cemented by manganese and iron oxides (hard pans); such layers are well seen in river bank sections [4672 4018] near Glanrhydypysgod. The compressible silts and clays which envelope the gravel bodies are commonly laminated and display layers of organic debris and rootlets. These finer-grained materials record overbank deposition from river or stream floodwaters. Lenses of highly compressible, organic rich clay mark the sites of abandoned meander loops (oxbow lakes), a recent example of which is seen at Dolau-uchaf [5162 4343], south-west of Llanybydder.

The principal tract of alluvium, that associated with Afon Teifi itself, commonly ranges up to 400 m in width and, exceptionally to the south-west of Lampeter, is over a kilometre wide. Narrower belts of alluvium occur within many of the tributary valleys notably those of the Afon Cych, Afon Ceri, Afon Tyweli, Nant Clettwr and Nant Cledlyn. These various tracts of alluvium will display a sheet-like geometry, with the thickness of alluvium along any stretch of river or tributary normally being equal to, or greater than the depth of the river or stream channel in that stretch. For the main river, therefore, alluvium thicknesses may regularly exceed 4 m; typical alluvium thicknesses in the tributary valleys will be less.

Alluvial fan deposits

Fan-shaped spreads of alluvial material, locally developed at the confluence of tributary streams and the main stream river, are described as alluvial fan deposits. Such deposits are typically contiguous and gradational with alluvium and comprise the same general suite of lithologies. However, the deposits of larger, low gradient fans, associated with some the principal tributaries of the Teifi as at Llanybydder and Lampeter, are likely to contain more finer-grained material those of smaller, steeper gradient fans developed at the confluences of some secondary tributaries.

River terrace deposits

River terraces are flat-topped, well drained platforms of differing height, which flank the modern floodplains of the Afon Teifi and its main tributaries, notably the Afon Cych and Afon Ceri. Each terrace marks the position of a former (higher) floodplain level within the catchment. They are underlain by river terrace deposits, which are mainly composed of gravel and sand. Boulder-sized clasts are common in the gravels, which include poorly sorted, structureless varieties as well as better sorted and cross-bedded units. Subordinate silts and clays are confined to thin beds and lenses. In general, river terrace deposits contain a much higher proportion of gravel and sand than the contiguous modern alluvium.

Up to three terraces have been recognised in any one stretch of the Teifi (or tributary), but it is uncertain whether the terraces can be correlated from one stretch to another. The higher gravel content of these deposits suggests that they were deposited under braided river conditions in contrast with the modern meandering river system. This is consistent with their formation during the early post-glacial period when river and sediment discharge, in response to seasonally melting ice and snow, was far greater than today.

The maximum thickness of terrace deposits in any one area will be equal to, or exceed the height of the various terraces above the modern alluvium. First terraces are commonly less than one metre above the modern floodplain; second terraces vary from 2 to 3 m above; and third terraces can range up to 5 m above.

Rare erosional terraces, cut in clayey till, have also been identified, as at [4704 4016], south of Glanrhydypysgod.

Lacustrine deposits

Lacustrine deposits occupy the sites of former, extant and drained ponds and lakes and comprise highly compressible, organic-rich clays and silts. Many small ponds are wholly, or in part artificial, and were created or enlarged within historical times. The deposits of these ponds are likely to be thin (<0.5 m) and to contain variable amounts of man-made artifacts. In contrast, the deposits which partially infill late glacial kettle holes, in the vicinity, for example, of Dolaugwyrddon [556 470] and beneath Llyn Pencarreg [5372 4563], the largest extant lake in the catchment, may be of substantial thickness (>2 m). In general, individual lacustrine deposits will display a lenticular geometry; thickest towards the centre of the deposit and thinning towards its margins.

Shoreface and beach deposits

Shoreface and beach deposits form Poppit Sands at the mouth of the Teifi estuary. There they comprise well sorted, unconsolidated shelly sands with subordinate gravels. They are subject to diurnal flooding and saturation by salt water and to vigourous disturbance by wave and tidal action. East of the main river channel, the surface of these deposits includes areas strewn with angular and rounded blocks and boulders derived from the adjacent retreating cliffs in glacial till. The offshore extent of these deposits is unknown. In central parts of the estuary, their thickness is likely to exceed the current 5.4 m tidal range, but towards the edges of the estuary much thinner shoreface and beach sands may veneer concealed rock platforms.

Tidal river deposits

Tidal river deposits represent the alluvial sediments accumulating in the tidal reaches of theTeifi estuary (Plate 3) between Cardigan Bar (Pen-yr-Ergyd) and Rose Hill. They comprise highly compressible organic-rich clays (mud) and silts with subordinate sands and gravel. They are subject to diurnal flooding and saturation by brackish water. The sand and gravel portions of the deposits relate to past and present river channel courses within the estuary.

Boreholes for the Cardigan Bypass bridge [1821 4592] penetrated 7.75 m of these deposits. Their maximum thickness is likely, at least, to equal the current 5 m tidal range at the mouth of the estuary, and to diminish up river.

Saltmarsh deposits

Rosehill Marsh [1888 4541] (Plate 3), an area of tidal river deposits which is extensively colonised by reeds and marsh vegetation, is distinguished separately as a saltmarsh deposit. The organic content of these marsh sediments is likely to be greater than other tidal river deposits. The maximum thickness of these deposits is unknown, but it is likely at least to equal the current 3 m tidal range for this part of the estuary.

3.2.2 Deposits of the last glacial period

Those drift deposits of the catchment which are inferred to have formed during the last glacial period fall into three categories (Figure 4): 1) those derived from a Welsh Ice Sheet. 2) those which relate to the Irish Sea Ice Sheet 3) the deposits of the putative proglacial Lake Teifi.

The deposits of the Welsh Ice Sheet contain subrounded to angular clasts dominated by Lower Palaeozoic rocks, principally mudstones and sandstones, consistent with transport by, and deposition from an ice mass originating in the upland regions of mid Wales. The clast assemblages of Irish Sea Ice Sheet deposits, in addition to local, Lower Palaeozoic rocks, contain well rounded clasts of far travelled exotic rock types with sources in Scotland, the Lake District, North Wales and the floor of the Irish Sea. These include Palaeozoic granites, Ordovician acid volcanics, Carboniferous limestones, cherts and coal, Permo-Triassic red sandstones, Cretaceous flints and Tertiary lignite; as well as abundant Pleistocene marine shells. The distinctive clays, which constitute the deposits of proglacial Lake Teifi, contain widely scattered, gravel-grade dropstones of both local and exotic rock types. On Map 1, the deposits of the Welsh and Irish Sea ice sheets are distinguished using the superscripts W and I respectively.

Glaciofluvial deposits, undifferentiated (Welsh)

Undifferentiated glaciofluvial deposits of Welsh ice derivation comprise generally well sorted and stratified sands and gravels. They form a series of well drained, degraded bench-like features, principally along the sides of the Afon Teifi valley between Cwm-cou [2930 4160], west of Newcastle Emlyn, and Llanfair [4340 4110], to the east of Llandysul, but also along some tributary valleys, notably the Afon Tyweli, south of Llandysul. The distribution of these deposits, extending well to the west of the speculated western limits of Welsh ice advance (Figure 2) argues against an ice-contact origin. They may represent the remnants of a late glacial outwash deposits or of deltaic bodies which were deposited within proglacial Lake Teifi (Figure 4d).

A gravel pit [3905 3908] at Pentre-cwrt exposes 3 m of these deposits; 10 m are exposed in a pit [4216 4114] east of Llandysul, but rapid lateral thickness variations are to be anticipated.

Glaciofluvial ice-contact deposits (Welsh)

Glaciofluvial ice-contact deposits predominantly comprise sands and gravels, but include clayey gravels and

Plate 3 Afon Teifi estuary [1823 4585], east of Cardigan, with Rosehill saltmarsh in the distance.

subordinate gravelly clays. Such deposits only occur east of Llandysul and are particularly widespread on both sides of the main river valley between Llanfihangel-yr-arth [4560 3980] and Llanwnnen [5330 4730]. Extensive deposits also occur on the north side of the river around Lampeter. In these areas they form a series of well drained mounds and sloping benches, which extend along the sides of the valley, but which locally spread across the main valley as near Glanrhydypysgod [4710 4030], and at Rhuddlan [4940 4280] and Pencarreg [5370 4570]. The bench-like landforms represent late glacial kames that record the accumulation material at the margins of melting valley glaciers. Where the deposits spread across the valley, they are interpreted as retreat moraines formed in front of the main valley glacier during pauses in its the eastward retreat (Figure 4e). The gravels include rounded to subangular, pebble, cobble and boulder grade clasts and vary from poorly to well sorted and from stratified to structureless. They represent predominantly water-lain or water-flushed material. Clay-rich parts of the deposits may represent flow and ablation tills, derived from the wasting ice and which escaped complete reworking and winnowing by melt water.

A gravel pit [5168 4419], west of Llanybydder, exposes over 8 m of these gravels, but the total thickness of the deposit here will be greater. In the vicinity of the giant kettle hole at Cilyblaidd [5372 4563], a thickness of 20 m can be demonstrated for the deposit. However, in other places isolated outcrops of solid rock, as at [4839 4264] to the southwest of Crug-y-whil, and at Ffynnonau [4704 4090], confirm the rapid lateral thickness variations which are likely to characterise these deposits.

Glaciofluvial sheet deposits (Welsh)

The catchment includes two geographically separate suites of Welsh glaciofluvial sheet deposits; between Lampeter and Llanybydder, and between Llandysul and Newcastle Emlyn.

Lampeter to Llanybydder

A series of distinctive, fan-like and terraced spreads of gravel and sand with subordinate silts border the modern alluvial tract south-west of Lampeter, and in the vicinity of Llanybydder (Plate 4). The fan-like geometry of these deposits is consistent with them comprising a series of alluvial fans supplied by braided, melt-water fed, tributary streams (Figures 2 and 4e). In contrast with the modern alluvial fans of the catchment, their surfaces display abundant kettle holes resulting from the melting of buried ice masses. The presence of kettle holes demonstrates that the deposits are of late glacial age. The kettle holes are commonly partially filled by lacustrine deposits. The well to poorly sorted gravels include rounded to subangular pebble, cobble and boulder grade clasts with sand or silt matrix and include stratified and structureless varieties. The gravels may pass laterally and vertically into cross-bedded sands. Clayey silts occur as thin beds and lenses. Cryoturbation features are widespread. Manganese oxide cemented layers, called 'Blackjack' by local farmers, are developed locally.

The thickness of these glaciofluvial fan deposits will vary. Where kettle holes are present, the depth of the kettles may provide an indication of the minimum thickness of deposit at any one site; kettles in the vicinity of Fferm Felinfach [5690 4635], for example, are locally over 4 m deep. The apex of a fan is likely to be underlain by a greater thickness of deposit than its flanks and fringes. However, 'windows' of the underlying till, for example to the south-west of Pentre-bach [5560 4715], illustrate the relatively thin nature of the deposit in some areas. River cliffs [5755 4700] north-west of Belli-coch provide a 5 m-high section in these deposits; manganese oxide cemented gravels are well seen along the edge of a landslip backscar 220 m to the west.

Llandysul to Newcastle Emlyn

The high glaciofluvial terraces present between Llandysul and Newcastle Emlyn comprise well sorted, stratified gravels and sands. They are interpreted as the remnants of a late glacial delta or outwash braidplain (sandur), which, prior to dissection by the modern river, once occupied the whole of the valley floor (Figure 4d). The maximum thickness of these deposits at any one site will be equal to, or greater than the height of the terrace above adjacent

Plate 4 Stratified glaciofluvial sheet deposits, river bank, 300 m north of Felinfach [5682 4665] (Note compass for scale is 10 cm long).

river terraces or alluvium, but the deposits are likely to thin rapidly towards adjacent valley sides.

A section in these terrace-like glaciofluvial sheet deposits is seen along Nant Bargod [3538 3970], where 5 m of bedded gravels are exposed.

Glaciolacustrine deposits (Welsh)

Sequences of interbedded clays, silts and sands with subordinate gravels, seen in the vicinity of Pentre-cwrt [3900 3780] and present at shallow depth beneath the wide alluvial tract south-west of Lampeter, record deposition to the front or to the side of deltas which built out into glacial lakes. The Pentre-cwrt deposits may represent an early glacial, prodelta sequence deposited at the margins of proglacial Lake Teifi, but the deposits near Lampeter formed within a much smaller, late glacial, meltwater lake (Figure 4d and e). Similar late glacial lake deposits are likely to occur below the wide alluvial belt southwest of Llanybydder and possibly also to the north-east of Maesycrugiau [4730 4130]. The clays and silts of these glaciolacustrine deposits are commonly interlaminated on a millimetre scale (varved). Interleaved with these laminated deposits are beds of silt and fine sand which may vary from several centimetres to several metres in thickness. Isolated, gravel-grade clasts within these finer lithologies are interpreted as dropstones.

These deposits are exposed in a section at [3802 3874] near Pentre-cwrt, where they are represented by 2.7 m of interbedded clays and sands.

Till (Welsh)

Welsh tills comprise compact diamicts which range from very poorly sorted, matrix-supported gravelly clays to clast supported clayey gravels. In both matrix supported and clast supported varieties, angular to subrounded clasts, predominantly of cleaved mudstones and sandstones, are set in a stiff, blue-grey, variably sandy and silty clay matrix. They represent material deposited directly from the Welsh Ice Sheet without any major flushing by glacial meltwaters. Tills in general are deposited by a variety of mechanisms. Lodgement till is material released from the base of an ice sheet and plastered onto the landsurface. Melt-out (or ablation) till is material rapidly dumped by melting ice. Flow till is material that flows from the surface of an ice sheet onto the landsurface. Though the Welsh tills are shown as undifferentiated till, any area of deposit may display internal variation which reflects these different modes of formation. Tills of Welsh ice derivation are restricted to east of Llandysul (Figure 2), where they give rise to irregular, poorly drained ground. The westernmost occurrences of these tills are confined to the sides and floors of narrow tributary valleys, notably those of the Afon Cerdin [415 420], Afon Tyweli [440 380] and Afon Clettwr [450 425], but from Maesycrugiau [473 413] eastwards, more extensive spreads are present. Their origin suggests that Welsh tills will be more extensive at depth and they probably underlie the main alluvial tracts of the Teifi and its tributaries and much of the glaciofluvial material within the eastern part of the catchment. The thickness of the tills is very variable ranging from a metre to in excess of 10 m. The thickest sequences may be present beneath the extensive spreads of Welsh till, south of Lampeter.

A farm cutting [5532 4618] at Dolgwm-Isaf provides a 3 m-high section in clast supported gravelly Welsh till.

Glaciolacustrine deposits of proglacial Lake Teifi

Distinctive, blue-grey to chocolate-brown, clays, widely encountered throughout the western part of the catchment, are interpreted as the deposits of proglacial Lake Teifi (Figure 4) (Plates 5 and 6). Outcrops of these clays are typified by a deeply gullied landscape. This reflects their highly impermeable nature, drainage being achieved almost exclusively by surface run-off. The easternmost exposures in these clays occur to the north of Mackwith, 2 km to the east of Llandysul, though there is anecdotal evidence from farmers of their presence in the vicinity of Maesycrugiau [473 413]. In the east, the clays crop out largely within the confines of the abandoned sectors of the preglacial Teifi valley and within tributary valleys. To the west of Llandygwydd [242 437], they crop out more extensively. They are believed to be present at depth below much of the modern alluvium of the Teifi and also to underlie large areas of the blanket of younger glacial

Plate 5 Glaciolacustrine clay (Lake Teifi), excavation [1731 4624] for Mwldan flood alleviation scheme, Cardigan.

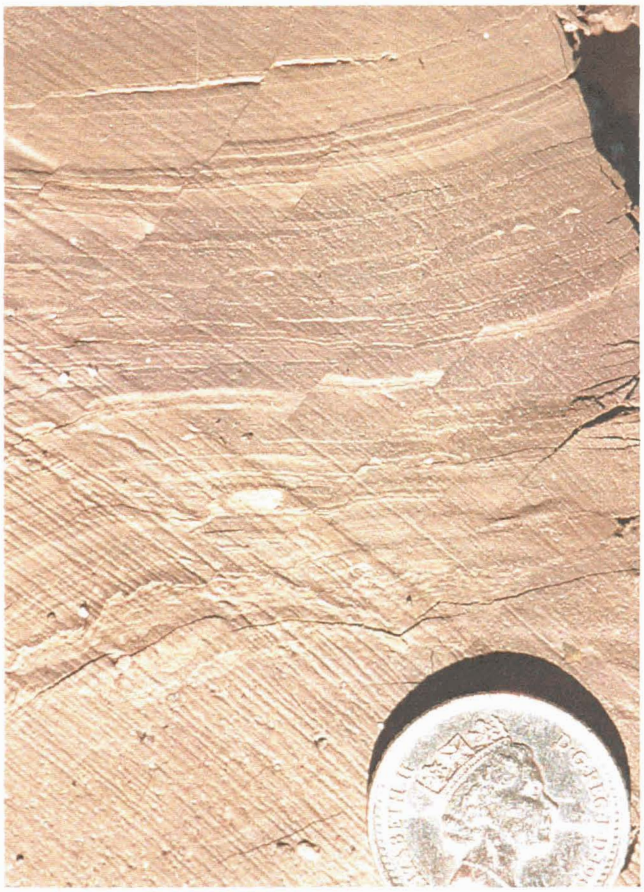


Plate 6 Laminated glaciolacustrine clay and silt (note small scale faulting dislocating paler silt layers), St Dogmaels landslide site investigation borehole, SDL 2, depth 42.5 m [1578 4544].

deposits present in the west (see schematic sections on Map 1). Scattered granule to boulder size clasts in the clays represent glacial dropstones. Rare silt and fine to coarse sand laminae are locally preserved.

Excellent sections in these glaciolacustrine clays were observed in excavations for the Afon Mwldan Flood Prevention Scheme [1731 4624], at Cardigan (Plate 5). They were also encountered in investigative boreholes for the St Dogmaels Landslip (Maddison et al., 1994) and in Cardigan No.1 and 2 boreholes (Appendix 3). The latter established sequences of these clays ranging up to 70 m in thickness within abandoned segments of the Teifi valley.

Glaciofluvial deposits, undifferentiated (Irish Sea)

Undifferentiated glaciofluvial deposits associated with the Irish Sea Ice Sheet generally comprise well bedded, unconsolidated (running) sands and gravels. They are confined to parts of the catchment west of Llandygwydd [242 437]. In the south and east of this region they occur as isolated deposits; more extensive spreads are present in the north around Penparc [210 480] and Ferwig [185 497]. The sands and gravels give rise to moundy, well drained ground in which the ice-contact and sheet categories recognised for the corresponding Welsh ice deposits cannot readily be distinguished. The gravels are typically cross-stratified, well sorted and comprise predominantly well rounded granule to cobble size clasts. The fine to medium-grained sands display cross- and parallel-lamination as well as larger scale cross-bedding. Both the gravels and sands contain abundant shell debris, and common clasts of lignite and coal. Subordinate clayey and silty gravels have been noted in some sections. These undifferentiated glaciofluvial deposits are thought to be predominantly of late glacial age and to include materials laid down and reworked by meltwater streams in a variety of settings both on and below melting ice as well as to the side and in front of the retreating ice sheet (Figure 4d).

Extensive sections are present in the Cardiganshire Sand and Gravel pit [2020 4847], near Penparc (Plate 7). The deposit in this area may locally approach 50 m in thickness. Sections in isolated sand and gravel bodies are provided by a gravel pit [1476 4530] near Foxhill (Plate 8), where up to 5 m of deposit are exposed, and by degraded gravel pits [2122 4368] at Llechryd. Boreholes and trenches put down by Crimes and Lucas (1992) sampled deposits near Foxhill [147 452] and Ferwig [185 497].

Plate 7 Glaciofluvial sand and gravel, Cardiganshire Sand and Gravel Pit, Penparc [2020 4847].

Plate 8 Poorly sorted glaciofluvial gravel, pit [1476 4530], near Foxhill.

Glacial and glaciolacustrine deposits, undifferentiated (Irish Sea)

These comprise variable sequences of interbedded clays, silts and sands with subordinate gravels. They underlie extensive areas of ground to the south of Cilgerran [190 408] and to the east of Llangoedmor [205 455]. Comparable deposits were also encountered in Cardigan No.1 and 2 boreholes (Appendix 3) and in the St Dogmaels site investigation boreholes (Maddison et al., 1994). Most are interpreted as glacial lake deposits which were laid down at the front or to the side of sandy deltas (Figures 4b and d), but some may represent glaciofluvial outwash. The deposits near Cilgerran and in the various boreholes appear to represent early glacial accumulations at the margins of proglacial Lake Teifi. The deposits near Llangoedmor, however, may relate to a later meltwater lake.

The clays are either structureless or interlaminated with silts (varved). Beds of silt, fine sand and gravel, from several centimetres to several metres in thickness, are also present. Isolated, gravel grade clasts within the finer lithologies are interpreted as dropstones. The deposits are distinguished from those derived from Welsh ice by the presence of dropstones of exotic rock types and shell debris.

In the Cardigan No.1 Borehole, 31.5 m of these silt-rich glaciolacustrine deposits were encountered, while 12.5 m were penetrated in the Cardigan No.2 Borehole (Appendix 3). The site investigation boreholes for the St Dogmaels Landslide (Maddison et al., 1994) established a 10 m-thick sequence. A borehole [2053 4559] near Llangoedmor penetrated 13.2 m of these deposits.

Heterogeneous glacial deposits (Irish Sea)

These deposits comprise a highly variable suite of predominantly well drained gravelly deposits including bedded sands and gravels and silty and clayey gravels, and subordinate gravelly clays. They pass gradationally into glaciofluvial Irish Sea deposits and Irish Sea till. They are confined to parts of the catchment west of Aber-banc [354 417] (Figure 2). In the east of this region they occur as isolated deposits; in central parts they form linear, bench-like features (kames) along the eastern side of tributary valleys, notably those of the Afon Ceri, Afon Hirwaun, Nant Pantgwyn and Nant Arberth; in the westernmost parts of the catchment extensive spreads occupy the high ground to the west of St Dogmaels. Sorting is very variable and poorest in the silt- and clay-rich gravels.

Plate 9 Ill-sorted clay and silt-bound gravel included in heterogeneous glacial deposits, cutting [2680 4173] behind bus garage, Cenarth.

Plate 10 Till (Irish Sea), comprising stiff stony clay, St Dogmaels site investigation borehole SDL1 (depth 4.1 m) [1568 4542].

Most of the deposits contain well rounded, local and exotic clast assemblages, but some, which have been derived from head gravels, are composed predominantly of angular local rock debris. Where they overlie bedrock, they grade downwards through angular head gravel into regolith. Heterogeneous glacial deposits record the reworking and mixing of earlier head and weathered solid material at the margin of the ice as it advanced inland. The bench-like kames, that flank the sides of tributary valleys, were deposited by meltwater flowing between the valley sides and the ice.

A quarry [1354 4927] a kilometre south-south-west of Cemaes Head, exposes 3 m of clayey gravels and regolith. A cutting [2679 4181] behind the bus garage in Cenarth (Plate 9) exposes 6 m of stratified gravels with beds of silty clay. In general, the origin of these heterogeneous deposits is likely to be reflected in rapid lateral thickness variations.

Till (Irish Sea)

Irish Sea till comprises stiff, ill-sorted, gravelly, sandy and silty, yellow weathering reddish brown clays with subordinate clayey gravels and thin cryoturbated sand and silt beds (Plate 10). Such tills are restricted to parts of the catchment west of Aber-banc [354 417]. In the east of this region they occur principally within the confines of tributary valleys, but in the west, around Cardigan, extensive spreads give rise to undulating, poorly drained and gullied ground. Clasts in the tills range up to boulder dimensions. Shell fragments are common. Small, irregular nodules of calcium carbonate are abundant in soil profiles developed in these clays and record the dissolution and reprecipitation of shell material. The deposits represent the basal till laid down by the ice sheet as it moved inland.

The tills are highly variable in thickness. Around Cardigan, site investigation boreholes for the Mwldan Flood Prevention Scheme encountered over 10 m of these deposits; 17 m were proved in the St. Dogmaels Landslip investigation boreholes (Maddison et al., 1994) (Plate 10). However, 'windows' of underlying glaciolacustrine clay show that elsewhere the till blanket of the Cardigan region locally comprises a superficial layer, in many places little more than a metre in thickness.

3.2.3 Older Alluvium

Older, pre-glacial river deposits are thought to occur at depth in the buried pre-glacial valleys of the Afon Teifi and are shown on the schematic sections included on Map 1. Gravels up to 4.3 m thick, encountered beneath glaciolacustrine clays in a borehole [1833 4606] for the Cardigan bypass bridge, have been classified as older alluvium. Elsewhere, the character, distribution and thickness of such deposits are almost entirely speculative.

4 Solid geology — Thematic Map 2

This thematic map shows the outcrop pattern of the principal solid rock divisions which are present in the project area. It also shows the location of the major faults which dislocate these rocks as well as providing information about the orientation of bedding and cleavage surfaces. Areas in which the solid rocks are mantled by drift deposits (see Thematic Map 1) are depicted with subdued colour.

The solid rock divisions within the catchment are all of Lower Palaeozoic age. They form parts of a sedimentary succession, comprising groups and formations, deposited during the late Ordovician and early Silurian periods, between 450 to 420 million years ago (Figure 5). All the formations and groups encountered in the project area predominantly comprise mudstones with variable proportions of sandstones. They are distinguished from one another by criteria such as bed thickness, bed internal structure, mudstone colour, the presence or absence of colour mottling, and sandstone/mudstone ratios. The nomenclature used for the various divisions largely follows that applied by the BGS elsewhere in mid Wales (Davies et al., 1997). The Moylgrove Group is used informally for strata, which include the Poppit Formation and St Dogmaels Formation of previous studies (McCann, 1992; Fletcher, 1994) as the validity of these formations as separate divisions is now suspect. The Nantmel Mudstones Formation broadly equates with the Tresaith Formation of Anketell (1987) and Fletcher (1994) and with the Mwnt Formation of Craig (1987). The generalised sequence of groups and formations, their internal variations and their estimated thicknesses, are summarised in Figure 5. By convention, these various divisions described below are in order of decreasing age.

All the rock divisions display the effects of ancient earth disturbances; they are pervasively folded and cleaved, and locally fractured, and have suffered low grades of metamorphism. These effects are assessed together in the section below dealing with geological structure. The effects of rock weathering are described in the section for Thematic Map 4.

4.1 MOYLGROVE GROUP (Moy)

This group is confined to the westernmost part of the catchment, where it forms the steep cliffs between Cemaes Head [132 502] and Poppit Sands [150 488] (Plates 11 and 13). A fault-bounded outcrop extends beneath St Dogmaels and the northwestern part of Cardigan. It comprises alternating sandstone-rich and mudstone-rich packets with the individual packets varying from five to several tens of metres in thickness. The sandstone-rich packets are composed of thin to very thick-bedded, tabular, fine to coarse-grained, dark brown sandstones and subordinate pebble and mud-flake conglomerates, interbedded with thin-bedded siltstones and medium grey to dark grey mudstones. Within these packets, individual sandstone beds range from less than 20 mm to more than 2 m in thickness, and the ratio of sandstone to siltstone/mudstone varies between 9:1 and 3:7. The mudstone-rich packets are composed of thinly interbedded, structureless, medium grey mudstones and laminated dark grey mudstones; widely scattered thin sandstone and siltstone beds rarely exceed 20 mm in thickness. Mudstones throughout the group are well cleaved and commonly rich in pyrite.

Graptolites recovered from laminated mudstones demonstrate a Caradoc Series (late Ordovician) age for the surveyed portions of the Moylgrove Group.

Sections typical of sandstone-rich parts of the Moylgrove Group are provided by the cliffs [1498 4890] by Poppit Sands and by a quarry [1633 4555] in St Dogmaels. Mudstone-rich parts of the group are well seen in the river cliffs [1638 4625 to 1648 4617] at St Dogmaels.

4.2 NANTMEL MUDSTONES FORMATION (Ntm)

Rocks of the Nantmel Mudstones Formation crop out beneath much of the western portion of the catchment; they form the cliffs north of the estuary at Gwbert [1624 4912] (Plate 12) and extend inland as far east as the vicinity of Bancyffordd. The bulk of the formation comprises well cleaved, pale to medium grey, and locally greenish grey, silty mudstones, which normally display distinctive dark grey mottling. Individual mottles vary from elongate to ovoid and subcircular in shape and range up to 10 mm in width and several centimetres in length. They are normally an obvious and readily recognisable feature of the mudstones, though in some areas mottling is poorly developed. Locally, where thin (<5 mm), closely spaced siltstone laminae are abundant, the mudstones appear thinly bedded. In contrast, where such laminae are rare or absent, the formation can appear very thickly bedded, with the spacing between obvious bedding plane partings commonly exceeding 2 m.

In the lower part of the Nantmel Formation, exposed in the west of the area, abundant units of thin to medium-bedded, tabular sandstones and structureless dark grey mudstones are abundant, interbedded with the normal mottled mudstones with siltstone laminae. In the uppermost part of the formation, which is seen in the east, packets of thinly interbedded structureless and laminated, dark grey, pyritic mudstones form distinctive units in the normal mottled mudstones (Figure 5). They compare closely with mudstones of the Moylgrove Group and exhibit comparable weathering characteristics. At least six separate packets have been identified, ranging from 2 m to 50 m in thickness. Graptolites collected from these units are consistent with an Ashgill Series (latest Ordovician) age.

Sections in the mottled mudstones of the Nantmel Mudstones Formation are provided by the Cilgerran Gorge [1898 4508 to 2125 4325], the A484 between Llwynduris [2352 4332] and Pontbren [2582 4246], and the Cenarth rapids [2693 4154] (Front cover). Parts of the formation with abundant siltstone laminae are particularly well seen in the cliffs [1608 5000 to 1623 4905] at Gwbert

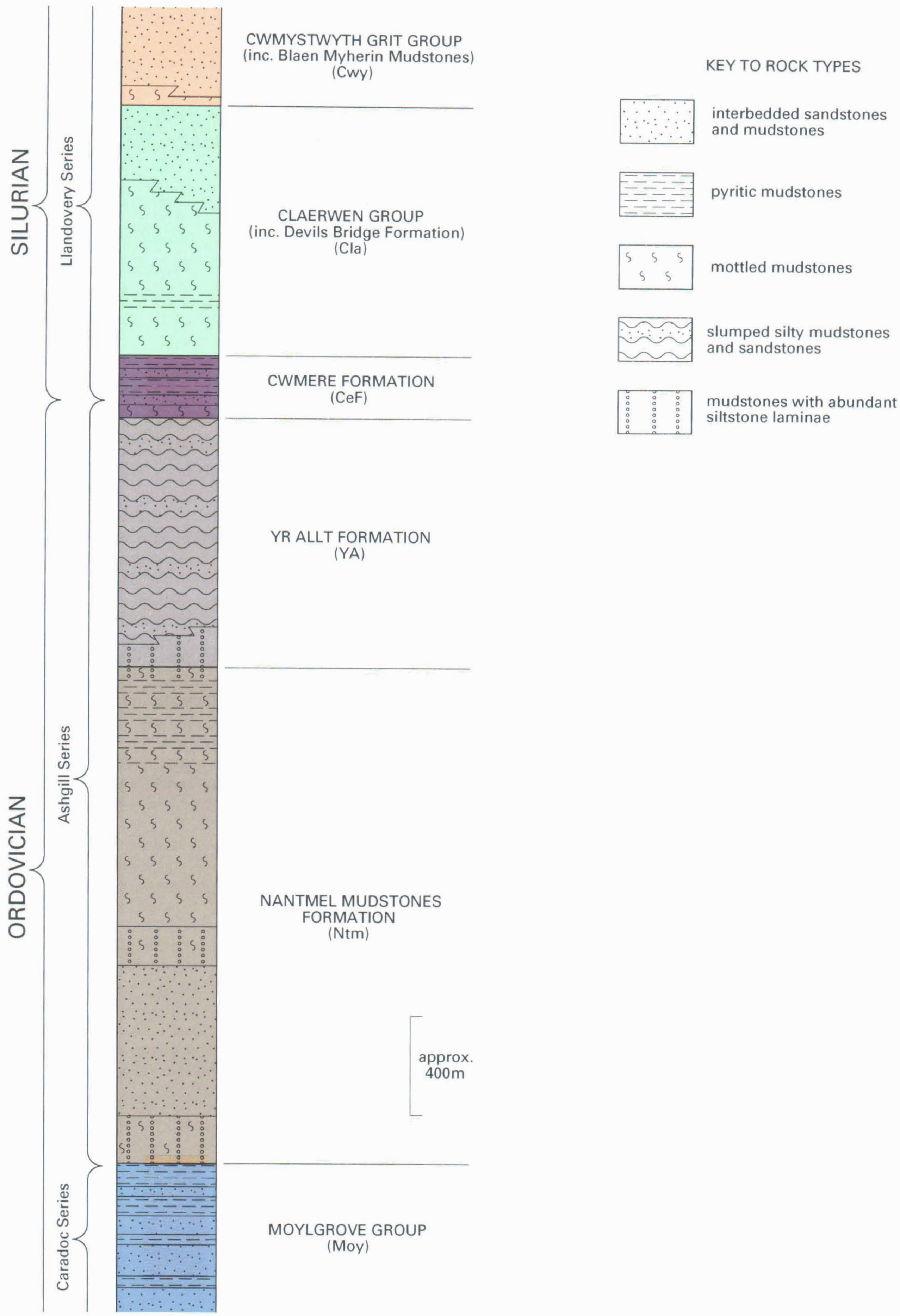


Figure 5 Solid rock succession of the project area.

Plate 11 Interbedded sandstones and mudstones of the Moylgrove Group, cliffs at Poppit Sands [1490 4890].

(Plate 12). The numerous quarries [1898 4508 to 1930 4444] in the Cilgerran Gorge exhibit that part of the formation with widely spaced bedding planes and very few siltstone laminae. A quarry at [1737 4802], west of Cardigan, affords a 15 m section in the western, sandstone-rich levels in the formation. Sections in the pyritic mudstones, in the upper part of the formation, are observed at Newcastle Emlyn [3108 4088 to 3058 4093] and Adpar [3102 4085 to 3145 4101].

4.3 YR ALLT FORMATION (YA)

Within the catchment, the Yr Allt Formation crops out between Llandyfriog [330 415], in the west, and the Maesycrugiau [474 413] area, in the east. It mainly comprises dark grey, very silty mudstones. Although some parts of the formation are well bedded, much of it exhibits the effects of slumping and sliding following deposition on the sea floor. In the slumped portions of the formation, bedding surfaces are typically poorly developed or absent; cleavage surfaces are irregular and widely spaced, and balls and lenses of siltstone and sandstone, ranging from <10 mm to over 2 m across, are locally present. Associated with these slumped mudstones, in the Maesycrugiau area, are packets of bedded sandstone tens of metres thick, in which individual beds of medium to coarse-grained, massive sandstone can exceed 2 m in thickness. Bedding surfaces within these sandstone packets exhibit complex folding and distortion.

In the well bedded parts of the formation, the mudstones are better cleaved and contain abundant, closely spaced siltstone laminae, typically less than 5 mm in thickness.

No fossils have been recovered from the formation itself, but it is both underlain and overlain by strata containing late Ashgill Series (latest Ordovician) graptolites.

Bedded parts of the formation are seen in sections at Llandysul [4116 4020] and [4190 4100]. Slumped mudstones with balls of sandstone are seen in crags [4624 4037], north-east of Llanfiangel-ar-arth. A quarry [4552 4111], south of Capel Dewi, affords a section in massive 3 m-thick sandstones; slump-folded sandstones are well exposed in cliffs [4720 4134] north of the river at Maesycrugiau.

4.4 CWMERE FORMATION (CeF)

In the main river valley, the Cwmere Formation crops out between Llanfihangel-ar-arth [458 398] and Alltyblaca [453 456]. Further outcrops traverse the Tyweli valley at Ty-Newydd [440 383] and Pencader [350 445]. The formation dominantly comprises thinly interbedded structureless and laminated, dark grey, pyritic mudstones (Plate 17) similar to those in the Moylgrove Group and parts of the Nantmel Mudstones Formation. At the base of the formation a unit of mottled mudstones, some 20 m to 30 m thick is present. Identical mudstones are present at this stratigraphical level throughout west and central Wales. At one or more levels within the formation, abundant medium to thin, tabular sandstone beds occur interbedded with the normal mudstones; at Alltyblaca [523 455], medium to coarse-grained sandstones over 1.5 m thick are exposed.

The basal mottled part of the Cwmere Formation contains a distinctive uppermost Ashgill Series (latest Ordovician) graptolite fauna. However, the bulk of the formation is known from elsewhere to contain graptolites of the Llandovery Series (early Silurian).

The basal mottled beds are well seen overlying the Yr Allt Formation in a quarry [4772 4030], west-northwest of Llanllwni, where the overlying mudstones are also exposed. A thin-bedded, sandstone-rich sequence developed in the lower half of the formation is exposed in the river cliffs at Rhuddlan [4953 4303] and in a disused railway cutting [4552 3955], at Llanfihangel-ar-arth. The thick sandstones at Alltyblaca are seen in a quarry [5226 4548] overlooking the river.

4.5 CLAERWEN GROUP (INCLUDING DEVIL'S BRIDGE FORMATION) (Cla)

The outcrop of the Claerwen Group extends from the vicinity of Aber-Giar [502 415] to the eastern boundary of the area surveyed. The main part of the group comprises thinly bedded, pale grey to green mudstones with diffuse siltstone laminae. Darker colour mottling, smaller than that observed in the Nantmel Mudstones Formation, is present locally. Thin, parallel-laminated siltstone and cross-laminated, fine grained sandstone beds are present to the east

Plate 12 Gentle fold (anticline) in thin-bedded and cleaved mudstones of the Nantmel Mudstones Formation, coastal cliffs, Gwbert, [1624 4912].

of Pencarreg [535 453] and Llanwnnen [533 473], and gradually increase in importance eastwards. Individual sandstone beds predominantly range from 20 mm to 150 mm in thickness, with the ratio of sandstone to mudstone varying greatly between 1:6 and, exceptionally, 1:1. These sandstone-rich levels equate, at least in part, with the Devil's Bridge Formation of other areas in mid Wales. However, in the surveyed portion of the catchment, the level of exposure has precluded separate delineation of this formation. Dark grey, pyritic mudstones comparable to those described from preceding formations form a subordinate part of the group, occurring as packets up to 20 m thick.

Graptolites recovered from the Claerwen Group and Devil's Bridge Formation confirm a mid Llandovery Series (early Silurian) age.

Sections in the grey and green mudstones of the Claerwen Group are exposed in a quarry [5194 4319] in Llanybydder. A quarry [5402 4552] to the east of Pencarreg exposes greenish mudstones with siltstone laminae and scattered thin siltstone and fine-grained sandstone beds. Sections in interbedded sandstones and mudstones, elsewhere typical of the Devil's Bridge Formation, are afforded by a farm quarry [5792 4644] north of Parc-y-rhos, a quarry [5435 4708] east of Llanwnnen, and a disused council quarry [5848 4875] in Lampeter.

4.6 CWMYSTWYTH GRITS GROUP (INCLUDING BLAEN MYHERIN MUDSTONES) (Cwy)

The Cwmystwyth Grits Group occupies a small area within the surveyed part of the catchment, to the south Cwmann [590 465]. The group comprises interbedded mudstones and sandstones. The mudstones are predominantly thin to medium bedded, medium grey in colour and structureless. Laminated, dark grey, pyritic mudstones are present locally forming beds less than 10 mm thick. The sandstones in the group are of two distinct types: thin beds of fine-grained, parallel and cross-laminated sandstone; and medium to thick beds of coarse-grained, structureless, muddy sandstone. The latter can exceed 2 m in thickness and are typically cleaved. In major sections the ratio of total sandstone to mudstone ranges between 1:6 and 2:1. Elsewhere in mid Wales, a sequence, up to 100 m thick, and composed dominantly of thin to medium-bedded grey mudstones (the Blaen Myherin Mudstones Formation) intervenes between the Cwmystwyth Grits Group and the Devil's Bridge Formation. Such a sequence is not exposed in the surveyed part of the catchment. It may or may not be present in this region. The Cwmystwyth Grits Group is of late Llandovery Series age.

A road cutting [5861 4615] and nearby quarries north of Coedeiddig, provide sections in strata typical of the Cwmystwyth Grits Group.

4.7 GEOLOGICAL STRUCTURE

The effects of the major late Caledonian (late Silurian to mid Devonian) earth movements are pervasive in all the solid rock divisions (Figure 3). The pressures and strains inflicted on the sedimentary rocks of the region during this event caused them to buckle and fracture (Plates 12 and 13). It also imposed planes of weakness (cleavage) in the mudstones, along which they can easily be split. It is the features acquired during this deformation, which commonly have the greatest impact on human activities. The orientation of bedding surfaces, fracture planes (faults and joints) and cleavage can have a direct bearing on the design of excavations for cuttings or quarries, on the quality and extractability of hardrock aggregate, and on the movement and vulnerability to pollution of groundwaters.

The rocks of the catchment are complexly folded on a variety of scales. Major, regional folds affecting the area, including the Teifi Anticline and Central Wales Syncline, have wave lengths of many kilometres (Davies at al., 1997). However, the outcrop patterns of the rock divisions within the catchment are predominantly determined by mesoscale folds, with wave lengths of one to two kilometres. Smaller scale folds with wave lengths of 50 m or less, are the ones most commonly observed in natural exposures and which will be encountered in new cuttings and other excavations. The trend of the axes of these various folds, irrespective of scale, varies gradually within the catchment, swinging from north-east–south-west, in the east, to east-north-east–west-south-west at the coast. Bedding plane dip vectors, normally directed at high angle to the fold axes, vary accordingly; north-westerly and south-easterly directed dips are prevalent in the east, whereas north-north-westerly and south-south-westerly dips become more common westwards. Both mesoscale and minor folds are commonly asymmetric in

Plate 13 Folded and faulted mudstones and sandstones of the Moylgrove Group, cliffs south of Cemaes Head [1300 4968] (note vegetated mass of slipped rock debris centre right).

profile with the bedding planes on one limb normally dipping at a steeper angle than the other.

Faults also occur on a variety of scales. Major faults, along which there has been substantial movement during more than one period of geological time, are associated with the outcrop of the Moylgrove Group around Cardigan, and with the Cwmere Formation at Llanfihangle-ar-arth [458 398]. These faults are not exposed at surface, but crush belts several metres wide with clay gouge and associated quartz veins can be anticipated along the course of these structures. Smaller faults with displacements of a few metres or less, are evident in many exposures, commonly affecting the axes of minor folds.

Both the mudstones and sandstones of the various rock divisions are locally well jointed. Joint directions appear highly variable, though systematic measurements have not been undertaken as part of the project.

The regional late Caledonian cleavage is evident in the mudstones of all the rock units and also affects the muddy sandstones of the Cwmystwyth Grits Group. The strike of the cleavage within the catchment is normally subparallel to the fold axes and varies accordingly between north-east–south-west and east-north-east–west-south-west. It typically dips towards the north-west or north-north west, but in a belt to the east of Cardigan, between Penparc and Beulah, the cleavage is commonly vertical or inclined towards the south-south-east.

The various effects of the late Caledonian deformation on the sedimentary rocks of the catchment are spectacularly demonstrated by the cliffs between Cemaes Head [132 502] and Poppit Sands [150 488], and in the cliffs on the north side of the Teifi estuary, below Gwbert [162 491]. Inland sections are provided by the Cilgerran Gorge [1898 4508 to 1930 4444] and the A484 road cutting at Newcastle Emlyn [3108 4088 to 3058 4093].

5 Mineral deposits and surface mineral workings — Thematic Map 3

This section describes those mineral deposits of the Afon Teifi catchment that may be considered as a resource. *Mineral resources* are natural accumulations of minerals or bodies of rock that are of potential economic interest, or which may become so. However, the identification and delineation of mineral resources is inevitably rather imprecise, as it is limited not only by the quantity and quality of the data currently available, but also involves predictions of future economic circumstances. The assessment of resources is therefore a dynamic process which must take account of geological re-interpretation, as well as the evolving demand for minerals, or specific qualities of minerals, due to changing economic, technical and environmental factors. *Mineral reserves* are those resources that have been fully evaluated and whose exploitation is commercially viable. They are not discussed in this report as their identification depends on a relatively expensive evaluation programme, involving detailed measurement of the material available for extraction, its quality, market suitability and the revenue its sale will generate. This activity is an essential pre-requisite for submitting a planning application for mineral extraction and, in the context of land-use planning, the term mineral reserve should be restricted to those minerals for which a valid planning consent for extraction currently exists.

The extraction of surface minerals commonly conflicts with the demands from agriculture, urban development and the environment. Factors to be considered by planners and developers include the potentially deleterious effects of mineral extraction on existing developments and the general environment and, conversely, the sterilisation of resources by new development. In addition, the restoration of abandoned mineral workings with unsuitable materials or methods of backfill, may lead to problematical ground conditions, which could inhibit future development of such sites or pollute groundwater.

The relationship between mineral reserves and resources (Figure 6) has been adapted by the British Geological Survey from a system of classification introduced by the United States Bureau of Mines and the US Geological Survey (McKelvey, 1972). In this conceptual diagram, the vertical dimension represents the economic viability of the resource and consists of two categories, *economic* and *sub-economic*, depending on whether or not it is commercially viable under prevailing economic conditions. As demand, mineral prices and costs of extraction may change with time, so mineral resources may become reserves and vice versa. In relation to this diagram, the mineral deposits of the Afon Teifi catchment are classified as *inferred mineral resources*, that have been largely defined from the available geological information. In general, they have not been evaluated by drilling or other sampling methods, and their technical properties have not been characterised on a systematic basis. **Additionally, the resources shown on the map take no account of the planning constraints that may limit their working.**

The mineral resources of the Afon Teifi catchment include those materials which are currently being worked, or have been worked in the past (glacial sands and gravels; glaciolacustrine clay; rock), as well as those identified during the recent survey as offering a resource potential (blown sand; river terrace deposits). Each of these deposits is described in turn below; their extent is shown on Map 3, which also gives an indication of where they have been worked at the surface. A list of these surface mineral workings, each of which generally exceed 1000 m^2, is provided in Appendix 5.

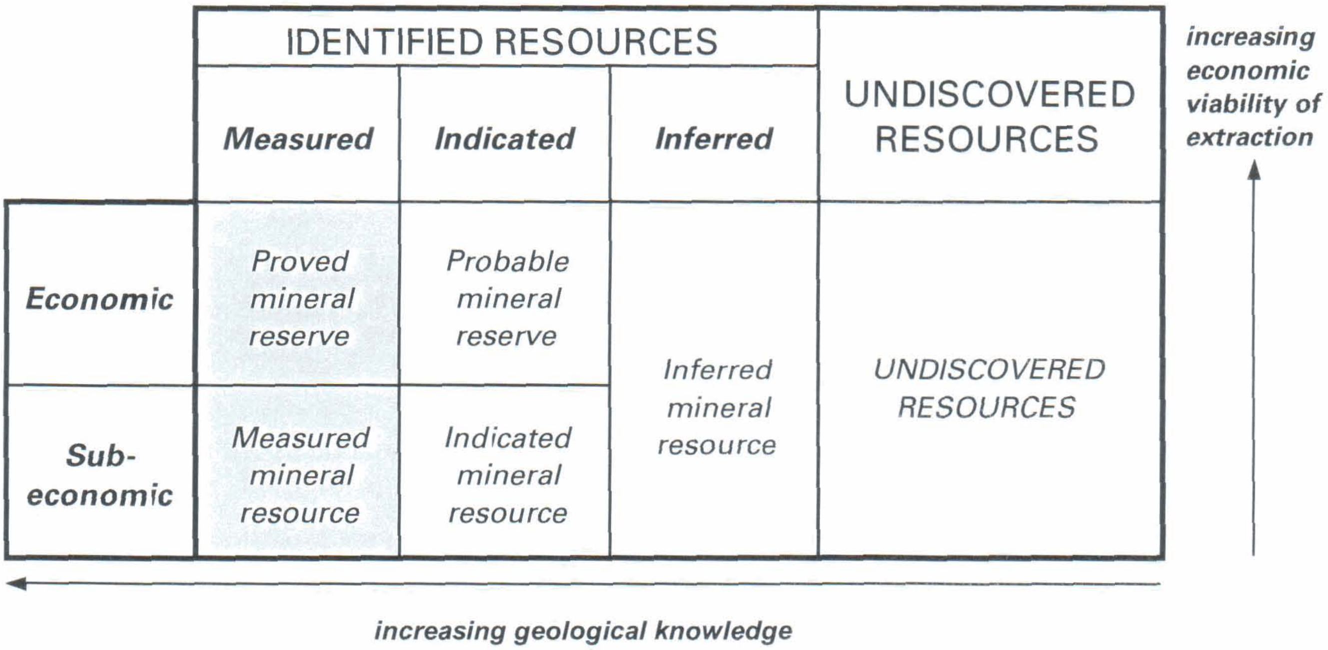


Figure 6 Classification of mineral resources (based on McKelvey, 1972).

5.1 SAND AND GRAVEL

The variability of sand and gravel deposits means that it is more difficult to infer the likelihood of potentially workable resources from geological mapping alone than for any other bulk mineral. The factors that influence this potential are the sand to gravel ratio, the proportion of fines and oversize material, the presence of deleterious rock types such as fissile mudstone and coal, the thickness of the deposit and its overburden, the position of the water table and the possible presence of unwanted material such as interbedded clays and till.

A previous study of the sand and gravel deposits of the region for the Welsh Office (Crimes et al. 1992) indicated two potential resource areas, lying mainly within the Afon Teifi catchment and partly within the currently surveyed area. These resource blocks (A and K; Crimes and Lucas, 1992), centred on Cardigan and Lampeter, were estimated to hold substantial deposits of glacial sand and gravel, mainly within kamiform mounds and ridges; minor resources were identified as river terrace gravels and blown sand. The work was based on only limited geomorphological mapping, supplemented by some drilling, and no systematic survey to determine the extent or quality of the deposits was undertaken. During the current survey, the detailed distribution of the resource has been established for the project area, and the deposits of sand and gravel have been shown to be even more extensive than the previous report suggested. The present study has also revealed the variability within these deposits, and has established a framework for detailed evalution of the resource in the area surveyed. Sand and gravel resources are present in the following Drift categories: Blown sand, river terrace deposits and glacial sands and gravels.

5.1.1 Blown sand

Deposits of wind blown sand blanket the glacial drift and solid formations around the mouth of Afon Teifi, the most extensive spread occurring at Towyn Warren on the northern side of the estuary. Although the dunes cover over 150 ha of this area, they rest on a highly irregular surface of older deposits and their thickness is therefore very variable. Detailed grading analyses of the deposits are lacking, but in general engineering/resource terms, they are seen to consist of poorly graded (i.e. well sorted), fine-grained, unconsolidated sands with some shell detritus. Their designation as a resource may be further restricted by environmental considerations, including tourism and conservation within the coastal tract. Much of Towyn Warren is an SSSI. There are no known workings within these deposits.

5.1.2 River terrace deposits

The post-glacial river terraces are developed at intervals along the Afon Teifi and in some of its major tributaries (e.g. the rivers Cych [250 410], Ceri [300 423], Clettwr [446 406], Tyweli [413 398] etc.). They generally comprise sands and gravels whose composition largely reflects the nature of the bedrock and glacial deposits eroded from within the catchment. Thus, they are mainly composed of Lower Palaeozoic materials (mudstone, siltstone and sandstone) derived from the Welsh uplands; a small proportion of igneous and metamorphic clasts, limestone and Triassic sandstones, from glacial material of Irish Sea origin, occur in the river terrace gravels towards the western end of the catchment.

The highest river terraces lie up to 5 m above the alluvium, and the deposits may, in places, extend under the modern alluvial tract. The total thickness of the resource is unproven, although it is likely that the deposits thin rapidly towards the valley sides. The sands and gravels are usually well graded and of good to intermediate quality, although their quality may be limited by the relatively high proportion of weak mudstone and siltstone clasts in some of the deposits. In addition, they may locally contain a significant number of oversized clasts that would require screening or crushing. In most areas the sands and gravels are also covered by a thin overburden of silt and clay.

Further constraints on exploitation of the river terrace deposits include man-made features such as roads and small settlements, which are commonly situated on terraces above the flood-prone alluvial tracts and have locally sterilised the resource. Natural features, such as the narrowness of the resource within the confines of the major valleys, and the proximity of the river with the attendant risk of flooding, may also restrict exploitation; for example, the lowest terrace, about 1 m above the alluvial floodplain, is commonly inundated during major flood events. Fluvial recharge through the gravels may also flood any workings, and it follows that exploitation below the alluvium would need special extraction techniques. As the river terraces (and alluvium) constitute a potentially important minor aquifer, care would need to be taken in protecting any groundwater sources from disruption or pollution. Designation of the area adjacent to the Afon Teifi as a potential future SSSI may also conflict with any planned extraction.

River terrace deposits have been worked to a limited extent for local supplies near Pont Bargod; the pit [3507 4038] is now abandoned and flooded.

5.1.3 Glacial sands and gravels

Glacial deposits provide the largest sand and gravel resource within the Afon Teifi catchment. They comprise the glaciofluvial deposits of both the Welsh and Irish Sea ice-sheets, together with ice-contact sands and gravels, and heterogeneous glacial deposits. Extensive spreads of these sands and gravels are present on the flanks of the Afon Teifi and in tributary valleys at the western end of the catchment, and they also underlie large areas of the main valley between Lampeter and Llanfihangel-ar-arth [456 399]. However, between Llanfihangel-ar-arth and Newcastle Emlyn they are only sporadically preserved, and they are generally absent from the Teifi valley between Llandygwydd [240 437] and Cwm-cou [293 420]. The deposits range from good quality, well-graded sands and gravels to poorly-graded clayey gravels, with intercalated till lenses. They fall into two broad categories of resource, namely, good to intermediate quality and poor to intermediate quality. There is however, complete gradation between each end member.

Good to intermediate quality sands and gravels

The undifferentiated glaciofluvial deposits derived from the Welsh and Irish Sea ice sheets, and the glaciofluvial sheet deposits of Welsh origin, are an inferred mineral resource of good to intermediate quality. The deposits associated with the Irish Sea Ice sheet are restricted to the western part of the catchment, where they form mounds and irregular spreads of sand and gravel. Those derived from the Welsh Ice sheet are largely confined to the Teifi valley east of Cwm-cou [293 420], occurring as terrace-like features or irregular mounds along the valley sides, becoming more widespread east of Llandysul; they are also preserved in tributaries such as the Afon Tyweli, south of Llandysul. In general, the deposits of Welsh origin are composed exclusively of Lower Palaeozoic mudstones, siltstones and sandstones, whereas those of Irish Sea origin contain a mixed assemblage of Lower Palaeozoic and 'exotic' clasts, the latter including granite, dolerite, lignite, coal, limestone and abundant shell debris.

The thickness of these deposits varies considerably. The glaciofluvial sheet sands and gravels are generally more constant in thickness, with at least 10 m preserved above the alluvium, and possibly more present below floodplain level; the extensive terraced spreads of gravel in the area around Lampeter may be of even greater thickness. In contrast, the undifferentiated deposits vary widely and often rapidly in thickness and altitude along valley sides. They are most widespread in the west of the catchment, where they locally exceed 50 m in thickness, having been worked in places on a large scale. In general, both the sheet deposits and undifferentiated glaciofluvial sands and gravels are moderately well graded to poorly graded, although considerable variability is often present within an individual deposit. Particle size grading curves for Irish Sea glaciofluvial materials reveal a wide grading envelope, indicating considerable variation of the deposit within the area (Appendix 4, Figure 32; Crimes and Lucas, 1992), with a preponderance of either sand-dominated or gravel-dominated lithologies; however, in some cases this may be an artefact of the sampling process, where only small and relatively dispersed analyses were undertaken for specific site investigations. Grading curves for Welsh-derived material within the present survey area are too few in number to draw any conclusions, although limited sampling from the area north of Lampeter, revealed relatively well-graded deposits, with a low percentage of fines (Crimes and Lucas, 1992).

Sterilisation of major gravel spreads, such as those at Newcastle Emlyn, and Lampeter has largely taken place, and developments at Penparc [202 485], Llandysul and Pencader [445 362] have probably restricted the exploitation of others. In general, the limitations imposed on the recovery of the remaining glaciofluvial sands and gravels are similar to those of the river terrace deposits. The presence of weak mudstones within both the Welsh and Irish Sea derived gravels, and the small but significant proportions of organic material (coal, lignite, shell fragments) in the latter will reduce the quality of the deposit, as will the dominance of oversize material in some horizons. Excavation of the glaciofluvial sheet deposits in the eastern part of the catchment, is likely to be impeded by kettle holes filled with lacustrine clays, and also by the hard, manganese-cemented layers within these gravels.

In addition to general environmental considerations concerning the large scale exploitation of sand and gravel within the Afon Teifi catchment, the glaciofluvial deposits also constitute an important minor aquifer which may require protection against pollution or disruption; the importance of this resource would therefore need to be balanced against the demand for sand and gravel within the region.

Glaciofluvial sand and gravel of Irish Sea derivation is currently being extracted on a commercial scale from within the catchment at the Cardiganshire Sand and Gravel Pit [2018 4844], Penparc (Plate 14) and for local consumption at Penralltcadwgan [1922 4086], south of Cilgerran. It was formerly worked commercially at the Cilmaenllwyd Pit [2044 4831], and to a limited extent around Llechryd at [2111 4355] and [2121 4370]; other disused workings were predominantly for local use. The Welsh-derived glaciofluvial sands and gravels are not being exploited commercially at this time, but were formerly worked from a number of small pits in the vicinity of Newcastle Emlyn and Lampeter, and are currently used locally for farm supplies.

Poor to intermediate quality sands and gravels

Extensive spreads of glacial sand and gravel, of poor to intermediate quality, occur particularly in the western part of the Afon Teifi catchment, and in the area north-east of Llandysul. They comprise the heterogeneous glacial deposits of the Irish Sea ice sheet and glaciofluvial ice-contact deposits of the Welsh Ice sheet. The heterogeneous glacial deposits of the Irish Sea ice sheet are mainly preserved in tributary valleys north of Cenarth and Llechryd, around Rhydlewis, and over a wide coastal tract between St Dogmaels and Cemaes Head. Those of Welsh derivation are predominantly ice-contact sands and gravels, which flank the Afon Teifi and its tributary valleys, notably the Nant Cledlyn [493 442] and Afon Grannell [530 480]. The Welsh deposits are characterised by the preponderance of locally derived

Plate 14 Cardiganshire Sand and Gravel Pit [2020 4847], Penparc.

clasts, whereas the Irish Sea deposits contain the typical mixed assemblage of local and 'exotic' material. Both suites comprise highly variable sequences of predominantly coarse clastic deposits, ranging from bedded glaciofluvial sands and gravels, to silty gravels and gravelly clays, intergradational with, and locally indistinguishable from till and head deposits; irregular, concealed bodies of till are also probably present within the deposits.

The thickness of the sands and gravels is highly variable and subject to marked lateral changes. Their quality also fluctuates rapidly from the well-graded to poorly-graded types, the latter containing a high proportion of fines or a significant number of cobble and boulder sized clasts. It is this variability which reduces the potential of these deposits as a resource. The additional factors involved in their assessment are broadly similar to those of the other sand and gravel deposits of the region; i.e. the proportion of deleterious rock types within the material, the amount of oversize clasts, potential risk to the local aquifer, any further sterilisation of the resource and general environmental considerations (amenity, landscape value etc).

There are no current workings within these deposits, although the ice-contact gravels of Welsh origin were formerly excavated on a limited scale at near Lampeter [5753 4894], Llanybydder [5166 4419], and at Troedrhiwfenydd [4077 4274]; the heterogeneous Irish Sea glacial deposits are generally unworked.

5.2 CLAY

5.2.1 Glaciolacustrine clay

The glaciolacustrine clays of the proglacial Lake Teifi (Plate 15) constitute a minor resource that was worked in the past for brick clay, and also for mixing with coal to provide a low-grade fuel; it was additionally used in certain areas to improve the quality of agricultural land. The clays are preserved throughout much of the Afon Teifi catchment, the most easterly occurrences being near Graigwrtheryn [4336 4010], east of Llandysul. They occupy the abandoned course of the pre-glacial Afon Teifi, and probably underlie parts of the present day river valley, as well as flooring many of its tributaries. They are more extensive to the west of Llandygwydd [245 438], where they are contiguous with the silts and clays of the Irish Sea glacial and glaciolacustrine deposits.

The working of glaciolacustrine clays for brick making has now ceased. It was of only minor importance historically, and then mainly in Cardigan, because of the local availability of stone for building purposes. It was probably the proximity to the centre of demand and the nearby port facilities, rather than the suitability of the clays, that were the principal factors in the situation of brick pits in Cardigan. The brickyards closed during the early 20th century, as a result of competition from large-scale operations elsewhere in the UK. The main brickpits were in the central part of the town, along Bath House Road [1790 4652] and on the site of the present King George's Field [1832 4659]. Small, long-abandoned workings in glaciolacustrine clays for local brick supplies, occur sporadically throughout the catchment (Appendix 5), although some of these clays were utilised for other purposes (see below).

In modern resource terms, the glaciolacustrine clays of the Cardigan area are unsuitable for brickmaking because of their relatively high stone content which, in the past, was removed by handpicking. Although the proportion of included clasts generally diminishes eastwards across the catchment, there are other factors which may limit the use of the clays for this purpose. These include the properties of the brick, where it is sold for architectural use and the aesthetic qualities of the fired product. Modern brickmaking technology is also highly dependant on raw materials with predictable and consistent shaping behaviour, firing properties and emission levels, and it is increasingly common for brickmaking plants to blend materials from a number of different sources. It is unlikely therefore, that the glaciolacustrine clays could be utilised without recourse to other materials, and the associated cost of importing or exporting clays in the quantities required would probably preclude such activity. Furthermore, the extent of local workable clay resources for brickmaking would probably not sustain modern, large-scale development, although it might support small-scale, specialist brickmaking concerns; however, the environmental problems of pollution from even relatively small brickmaking plants may prove to be unacceptable.

The general impermeability of the glaciolacustrine clays probably make them a suitable material for lining or sealing landfill sites and other repositories. In situ clays may also offer suitable sites for the containment of waste. Clays from a site on the western outskirts of Newcastle Emlyn [3037 4150] have been utilised for this purpose, although initially their excavation was in order to stabilise a landslip. Most of the clay has been employed as fill elsewhere in the area, for which it is probably unsuitable, but a proportion has been used to cap a nearby tip [3007 4158], and some has been used to line an oil refinery slurry lagoon. Any use of clay for this purpose, would require care in controlling the proportion of silt and clast-sized material, particularly scattered boulders, and suitable site investigation would be needed for any *in situ* containment in these deposits.

The glaciolacustrine clays which were worked at Pentrecagal [3396 3999] were utilised as a bulking agent, for mixing with coal washings to produce a cheap, low-grade fuel. The pits have long been abandoned, and there is no foreseeable future demand for this use of the material.

5.3 SOLID ROCKS

The Ordovician and Silurian mudstones and sandstones have traditionally been quarried throughout the region as a building stone, a local roadstone, or a source of fill (Appendix 5). Although most rock formations have been worked for building stone at one time or another, not all horizons were suitable as building stone, the common requirements being for the well-bedded sandstones, or mudstones with well-developed bedding and cleavage partings that could be worked as 'freestone'. Pyritic horizons within the mudstones were generally avoided because of their tendency to flake and rapidly weather (see Plate 17). It is unlikely that stone for building will constitute a major resource in the future, but it will probably continue to be used on a small-scale for ornamental work and restoration.

The potential future sources of crushed rock for roadstone are confined to the localised developments of sandstone that occur at intervals throughout the Ordovician and Silurian succession. Horizons of thick sandstones are common within the Moylgrove Group, the upper part of the Yr Allt Formation, parts of the Cwmere Formation and the Cwmystwyth Grits Group. Although the extent of this resource is unproven in the Afon Teifi catchment, comparable sandstones with moderately high PSV's (62),

Plate 15 Excavations in glaciolacustrine clay (Lake Teifi), Mwldan flood alleviation scheme [1731 4624], Cardigan.

suitable for use as road surfacing aggregate, are worked at Dinas Quarry [627 354] near Llansawel, and Foelfach Quarry [391 257] south of Cynwyl Elfed. However, the economic potential of the sandstones is limited by their impersistent nature, internal variability, and their remoteness from major aggregate markets; therefore, it is likely that their future use will be only for local supplies.

Most of the mudstones and sandstones of the region are inert, and will continue to be used as a ready source of fill. However, the Moylgrove Group, parts of the Nantmel Mudstones Formation, and most of the Cwmere Formation contain pyritic mudstones that, on weathering, may cause heave and concrete attack. For this reason, they are unsuitable and should be avoided if possible.

The upper siltstone-poor part of the Nantmel Mudstones Formation has been worked in the past for flagstones and roofing slate, mainly in the Cilgerran gorge [193 446] (Plate 16), where they were transported down river to Cardigan. This industry has long since ceased.

5.4 RECOMMENDATIONS FOR PLANNING AND DEVELOPMENT

The glacial sands and gravels of the Afon Teifi catchment are considered to be a future mineral resource which requires further investigation and possible protection; river terrace gravels and blown sand are likely to be of only limited potential, except where worked in conjunction with the glacial deposits.

The present survey has generally confirmed the findings of the Welsh Office study (Crimes and Lucas, 1992), namely that the principal resource areas for sand and gravel are around Cardigan and in the Teifi valley north-east of Llanfihangel-ar-arth. The area between Llanfihangel-ar-arth and Newcastle Emlyn contains relatively small, isolated bodies of glacial sands and gravels and is, thus, of only secondary importance. Contiguous sand and gravel resources, previously identified in the Welsh Office report, undoubtedly spread beyond the currently surveyed area, although their overall extent is still poorly known. Therefore, it is recommended that the mapping of these deposits should be completed before evaluation of the resource is undertaken.

Although the potential for the glaciolacustrine clays as a landfill liner requires investigation, they are not currently regarded as important in resource terms, and it is unlikely that they will become so in the near future, except at local level. Likewise, the solid rocks are considered to be relatively unimportant as a regional resource, and do not merit further investigation at this time.

Plate 16 Disused slate quarry in Nantmel Mudstones Formation, Cilgerran Gorge [2040 4286].

6 Engineering properties — Thematic Map 4

Good land for building and construction is a valuable resource, and a knowledge of ground conditions is important for planners to identify land suitable for development. Such knowledge underpins cost effective design, efficient site investigation and safe construction in all forms of privately or publicly funded development, including housing, road building, water and sewerage pipelines and coastal defence works. The following section provides a general description of the ground conditions encountered in the project area, in terms of the engineering behaviour of the solid and drift deposits. It is intended to provide general guidance only, when used in conjunction with the relevant thematic map and other sections of this report. The variability in ground conditions, which may occur even over small sites, means that a study of existing site information, followed by careful and appropriate site investigation, should be undertaken prior to any development.

Engineering ground conditions in the catchment vary markedly from place to place, depending on the physical and chemical properties of the local geological materials, the topography, behaviour of groundwater and surface water, and the nature of past and present human activity. For example, the characteristics of areas with bedrock at outcrop differ greatly from those where there is a cover of thick superficial deposits. Man-made deposits such as waste tips and infilled land or embankments may give rise to particularly difficult ground conditions, and are a matter of some importance because such deposits are abundant in urban and marginal urban settings, where building and construction activity is concentrated.

Descriptions of the engineering ground conditions associated with the bedrock, natural drift and artificial deposits in the catchment are based on data which were obtained during geological mapping, from existing site investigation reports, and from published data for comparable deposits or rock formations in other areas. Geotechnical data from site investigations within the Afon Teifi catchment include the results of particle size analyses, Atterberg limits, undrained strength, density, moisture content and Standard Penetration Tests (SPT); some chemical test results are also included. These are presented as a geotechnical database (Appendix 4), together with the methodology used to derive the information and an assessment of its limitations. Summary results for particular materials are given below. Wherever possible, the terms and measurements used follow the recommendations of the Association of Geotechnical and Geoenvironmental Specialists.

6.1 ENGINEERING CLASSIFICATION OF SOILS AND ROCKS

For engineering purposes, the geological materials of the catchment are divided into 'soils' and 'rocks'. In general terms, engineering soils comprise the drift deposits shown on Thematic Map 1, which can usually be excavated by digging. Engineering rocks consist of the harder, more competent bedrock strata, shown on Thematic Map 2, which, unless highly weathered, usually require a more vigorous means of excavation. Within this broad two fold division, the engineering soils and rocks are grouped on the basis of lithology and similar geotechnical characteristics into 'engineering geology units'. It is these units which form the basis for the description of the engineering ground conditions in the project area, and which are portrayed on Thematic Map 4. However, it should be understood that any attempt to classify natural deposits in this way represents a 'best fit' approach which is necessarily subjective; it seeks to impose an artificial order to materials which are, in reality, highly variable and intergradational in both their composition and behaviour.

Generalised representation of the engineering ground conditions

Four of the most important considerations in terms of construction and development are the suitability of the ground to support structural foundations, the ease with which it can be excavated, the suitability of the ground materials for use in engineered earthworks and fills and the stability of slopes. The relevance of the first three factors for each of the engineering geological units are discussed below and summarised in the key to Thematic Map 4. Slope stability is discussed seperately in Section 8. The wide variety of engineering ground conditions which exist across the area can be addressed only in general terms in this study, and the degree to which detail can be presented is limited by the scale of the thematic maps; at the present 1:50 000 scale, the maps show only very generalised information. More detailed information on ground conditions can be derived from the larger, 1:25 000 scale geological maps which have been produced as part of the project, and from the geologist's 1:10 000 scale field slips. However, although these larger scale geological maps allow more accurate location of specific areas of interest, they remain as a guide only. **They cannot by themselves, or in conjunction with the other thematic maps, be used as a substitute for appropriate site specific ground investigations, but they should be consulted as a matter of course during pre-design feasibility studies and during the formulation of site investigation strategies.**

6.2 ENGINEERING SOILS (superficial deposits)

This group covers over sixty percent of the project area, and includes all categories of natural drift deposit, as well as landslipped material and man-made deposits. The natural drift deposits consist of 'cohesive' and 'non-cohesive' soils, and 'organic' soils. The glaciolacustrine clays of proglacial Lake Teifi, which present unique engineering characteristics, are the only materials classified as a wholly cohesive engineering soil. Many of the other superficial materials comprise mixtures of variable lithologies, because of the processes by which they were deposited, and collectively form the large group of 'mixed cohesive/non-cohesive' soils. Even the group of 'non-cohesive' soils, although dominated by sands and gravels, may contain impersistent layers of clays and silts. Organic soils consist of peat, recent lacustrine deposits and salt marsh deposits.

Thickness and variability of the engineering soils

The engineering soils exhibit considerable variations in thickness throughout the catchment, ranging from thin (<1.5 m) veneers on valley slopes, to thick accumulations of highly variable deposits infilling buried valleys, in places to depths of over 70 m below ground level (see Thematic Map 1). These variations will have an important influence on engineering ground conditions from place to place although, in general, there is insufficient data to comment on their thickness in anything other than the broadest terms. Furthermore, the distribution of the various engineering soil groups shown on Thematic Map 4 only indicates the nature of the material present at the surface; there is usually insufficient information to indicate regionally where layers or lenses of other engineering soil types occur between those exposed at the surface and the bedrock interface. Materials other than those shown at the surface may be anticipated, for example, below alluvium and within till deposits, both of which are known to contain lenses of sand, gravel and laminated silt-clay in places, within predominantly clay-rich material. Some of the potential relationships between superficial deposits in various parts of the catchment are shown in the schematic sections included on Thematic Map 1.

The thickness and subsurface variation in engineering soils will need to be ascertained as part of the investigation of individual development sites.

Shrinkage/swelling of clays

Shrinkage of clay soils may result from a reduction of soil moisture due to prolonged dry periods and/or the proximity of trees. Current practice in identifying potentially shrinkable clays relies on the measure of plasticity index; low, medium and high shrinkage potential is indicated by plasticity indices of 10–20%, 20–40% and >40%, respectively (National House Building Council, 1995). On this criterion, the clay soils of the Afon Teifi catchment generally fall into the category of low to medium swelling potential (Appendix 4). High swelling potentials have been recorded for the cohesive soils, although median values for these materials also fall within the field of medium shrinkage potential. Shrinkage may, therefore, pose a local problem during periods of prolonged drought, particularly in areas of the catchment underlain by either cohesive or mixed cohesive/non-cohesive soils. An assessment of shrinkage potential should be carried out during site investigations for shallow foundations on these deposits, and, where necessary, proper guidelines should be followed to ensure appropriate foundation design and placement.

6.2.1 Cohesive soils

These are restricted to the glaciolacustrine deposits of proglacial Lake Teifi. These glaciolacustrine clays (Plate 5) are widespread at surface throughout western portions of the project area, and underlie many other drift deposits. Thick sequences occupy the abandoned segments of the pre-glacial Teifi valley, and are suspected to underlie parts of the wide alluvial tracts of the present-day Afon Teifi and its tributaries. They were encountered in both of the boreholes drilled during the project (Appendix 3) and in site investigations at St Dogmaels (Maddison et al., 1994), Cardigan (along the Afon Mwldan) and Newcastle Emlyn. They mainly comprise highly impermeable, soft to stiff, homogeneous clays, with laminae of silt or fine sand in places; widely scattered gravel, cobble and boulder sized clasts are also present. These deposits interdigitate with the more variable (and generally more silty) glaciolacustrine deposits containing material derived directly from the Welsh and Irish Sea ice sheets, which are included in the mixed cohesive/non-cohesive soils.

Engineering properties (see also Appendix 4)

Nearly fifty percent of all known landslips within the catchment are associated with the presence of these clays, either at surface or at depth. Slopes greater than 1 in 20 within these materials should therefore be regarded as only marginally stable, with a high potential for failure, particularly when excavated or loaded during construction. The clays are of low to high plasticity (Appendix 4; Figure 34), indicating a low to high shrinkage potential. They locally exhibit slow to relatively rapid lateral flow, due to the low residual strength associated with their local high plasticity. Laminated varieties are also likely to exhibit highly anisotropic, and particularly low horizontal shear strengths. The clays show a trend of decreasing strength with depth (Appendix 4; Figure 36). This is normal for such deposits, where near-surface desiccation and the development of hardpan contribute to strength.

The highly impermeable nature of the clays may give rise to severe site drainage problems during and following construction.

Design Considerations

i) Foundations

The problems likely to be encountered with foundations in the glaciolacustrine deposits (Plate 15) include variable bearing capacities and compressibilities of the clays, perched groundwater tables and water uplift pressures, and the likelihood of excessive total and differential settlements. Site investigations, often requiring closely-spaced boreholes, should aim to ascertain the presence, depth and extent of soft compressible zones and the depth to sound strata. Although lightweight structures founded on the harder desiccated surface layer of these clays appear to experience few short term problems, medium to longer term settlements may be anticipated.

Where limited thicknesses occur, wholesale removal and replacement of the glaciolacustrine clays with suitable fill may be an economic option, but elsewhere alternative solutions are required. Of these, piling and raft foundations are the most commonly used. For heavy structures, bored or driven piles should be used to transfer loads to underlying dense gravels or bedrock. For piles in thicker deposits, consolidation of the clays may cause 'drag-down' of the loaded pile and this should be anticipated. Raft foundations may be successful for light structures, with large settlements accounted for in design. Very low rates of consolidation settlement may be partly overcome by the use of lightweight fill or by staged surcharging, for both structures and embankments.

ii) Excavatability and stability of cut slopes and excavations

Although the clays are diggable, medium term support is normally required to maintain the stability of trench sides and cut faces. Excavations in softer parts of these deposits may require immediate support. **It should be noted that**

whatever the excavated material, there is a legal requirement to support all trenches over 1.2 m deep if access to them is required. Water inflow from overlying aquifers, and artesian ground waters escaping from breached, underlying aquifers are known to have caused severe problems at particular sites. The effect of any excavation on the stability of adjacent slopes needs to be carefully assessed.

iii) Suitability as engineered fill

Glaciolacustrine deposits are generally unsuitable for use as fill. Soft, highly plastic parts of the deposit will be prone to large deformation by heavy plant.

6.2.2 Mixed cohesive/non-cohesive soils

This large group comprises deposits in which cohesive and non-cohesive materials are interbedded, or those which are so variable, that cohesive and non-cohesive materials are randomly distributed and intimately associated on a variety of scales. The deposits have been subdivided on the basis of the compactness/relative density of the dominant materials into four main engineering geological units: i) stiff/dense soils, ii) firm/dense soils, iii) interbedded soft-firm/loose-dense soils and iv) soft/loose soils. Although the last three categories of soils are described separately below, they are intergradational in terms of their engineering properties, and for this reason have not been shown separately on Thematic Map 4. The corresponding drift deposits are shown separately on Thematic Map 1, and in greater detail on the 1:25 000 scale geology maps of the area. The extreme variation within these mixed soils means that the general statements made below should not be taken as diagnostic of entire deposits, either at surface or at depth.

6.2.2.1 Stiff/dense soils

This group comprises Irish Sea and Welsh tills and heterogeneous glacial deposits. Till (often referred to as 'boulder clay') typically comprises blue-grey or brown, stiff to very stiff, sandy and silty clay with included sub-rounded pebbles, cobbles and boulders of rock (Plate 10). In places, it contains irregular and impersistent layers of laminated clays, silts, and dense sands and gravels, whose extent is difficult to determine without detailed, closely-spaced subsurface investigation. Heterogeneous glacial deposits typically comprise illsorted boulders and cobbles in a variable sandy or clayey matrix, but can be highly variable and include till-like material as well as thick beds and lenses of loose sand and grave (Plate 9).

Engineering properties (see also Appendix 4)

Till may be soft to firm within 1 or 2 m of the ground surface, due to weathering, but in some cases a fissured, firm to stiff, desiccated surface zone may be developed above a softer layer, which gradually becomes stiffer with depth. Depending on the sand/silt content, the till matrix consists of clays ranging from generally low to medium, and occasionally high plasticity. Compressibility is generally low, but consolidation settlements may be high in softened till adjacent to water-bearing sand and silt layers or lenses. It is unlikely that heterogeneous glacial deposits were ever subjected to substantial ice-loading and therefore their engineering behaviour may be more akin to gravelly, clayey head rather than overconsolidated till. Recorded plasticity indices for clayey till generally range from about 10–30%, indicative of soils with low to moderate shrinkage potential (Appendix 4; Figure 34); highly shrinkable soils are unlikely to be encountered in till.

Design Considerations

i) Foundations

Till deposits should present no major foundation problems, provided thickness and lithological variations (particularly the presence of water-bearing sand and gravel layers, and lenses of laminated silts and clays) are determined during site investigations and accounted for in design. For example, water-bearing sands and gravels below foundation levels in clayey till may cause softening and/or heave, due to artesian conditions. Where development is planned on moderately steep slopes, care should be taken to ascertain current stability conditions of till deposits and the likely effects of excavation and construction. In general, heterogeneous glacial deposits will exhibit similar ground conditions to till, although their greater variability requires that more detailed investigations are undertaken. Ground conditions within beds of loose sand and gravel associated with these deposits will be similar to those of non-cohesive soils (see below).

ii) Excavatability and stability of cut slopes and excavations

Till may be machine-excavated with the prospect of hard digging in very stiff, over-consolidated material with included cobbles and boulders. Ponding of surface water in low permeability boulder clay may cause problems during working. Temporary cuts or excavations in 'homogeneous' boulder clay should remain stable in the short to medium term, and possibly in the long term in low cuttings. The presence of lenses of laminated silts and clays will considerably reduce stability, as will sand and gravel horizons with perched water tables and increased seepage. Where these materials are exposed in excavations, immediate side support may be required.

iii) Suitability as engineered fill

Till may be suitable as fill if care is taken in selection and extraction. Because of lithological variations, selection of suitable material will need to be made on a site-specific basis. Laminated silts and clays, which occur locally within the till, are usually unsuitable for use as fill. Clayey till occurring near water-bearing beds of sand and gravel may be similarly unsuitable.

6.2.2.2 Firm/dense soils

These comprise head and head gravel, which embrace a range of poorly sorted, poorly consolidated deposits formed by the slow downslope movements of materials due to present day hillcreep and previous periglacial freeze-thaw processes. In general, head is derived from other natural superficial deposits and reflects their composition and variability. Head deposits most commonly comprise soft to firm sandy, silty clays or clayey silts, with scattered stones and cobbles. Head gravel (Plate 2) ranges from gravelly silty sands to stratified, clast-supported clayey sandy gravel, in which angular mudstone fragments are the dominant clast type; these deposits are typically derived from weathered mudstone bedrock. Head gravel commonly forms an extensive cover on the lower slopes of all the exposed areas of bedrock, usually as a thin veneer less than a metre thick; however, greater thicknesses have locally accumulated at the foot of slopes and in hollows, and thicknesses ranging up to 3 m have been recorded. The distinction between in situ weathered bedrock and head gravel is at times indeterminate, as one commonly grades into the other. However, in contrast to the weathered in situ soils, deposits of head gravel tend to be more variable, generally with lower shear strengths, and likely to contain, or be bounded by, shear planes having reduced strength.

The mapped distributions of head and head gravel generally greater than about 1 m thick, are shown on Thematic Map 1, but this is not fully representative. They can be assumed to occur elsewhere as a patchy veneer of varying thickness, which should be determined prior to the design of foundations or cut slopes.

Engineering properties (see also Appendix 4)

In general, clayey head deposits are likely to include a greater proportion of cohesive material, whereas head gravels may include a significant proportion of non-cohesive material (but see comments on these materials in Appendix 4). In both deposits, the low shear strengths are commonly due to the presence of relict shear surfaces, which developed during sliding associated with freeze-thaw processes. Such deposits are often only marginally stable and prone to landslip, even on shallow slopes, if stability conditions are adversely affected by excavations or loading. Site investigations should therefore aim to establish the extent, thickness and nature of head deposits so that stability conditions can be determined prior to site work.

Clayey head displays low to intermediate plasticity; data for head gravels suggest a low to high plasticity, but this may reflect the property of clayey matrix material rather than the deposit as a whole (see Appendix 4).

Design considerations

i) Foundations

Head deposits usually offer poor foundation conditions due to their variable thickness and composition, the possible presence of soft, compressible zones, and their generally low shear strength. Where feasible, head deposits should be removed prior to placing foundations. Their thickness (usually less than 1.5 m) often enables economic removal, but on sloping sites, care must be taken to ensure that the stability of these deposits is assessed prior to excavation.

ii) Excavatability and stability of cut slopes and excavations

Head deposits are easily excavated by mechanical digging. Clayey head is generally of very low permeability, and may cause problems during working due to ponding of water in depressions. Until proved otherwise, head deposits should be considered as marginally stable. Where relict shear surfaces are present, shear strengths on these surfaces will be at or near residual values, and this should be accounted for in slope design calculations.

iii) Suitability as engineered fill

Head deposits may be suitable as bulk fill but, locally, may be too wet to achieve satisfactory compaction.

6.2.2.3 Interbedded soft-stiff/loose-dense soils

These deposits comprise glacial and glaciolacustrine deposits of Welsh and Irish Sea ice derivation. They contain cohesive, silt-laminated glaciolacustrine clays, identical to those assessed above, interbedded, on a variety of scales, with non-cohesive silts and fine sands, and, locally, loose to dense gravels. They occur in three principal areas, to the east of Llangoedmor [210 460], south of Cilgerran [190 420] and at Pentre-cwrt [390 388]. Similar deposits underlie the wide alluvial tract at Lampeter, where they have been proved in boreholes, and they may occur in comparable subsurface situations down-valley. Sequences of these deposits, up to 30 m thick, were encountered in the Cardigan No.1 Borehole [1768 4764] (Appendix 3, Figure 28). The strongly contrasting properties and close association of the differing materials in these deposits means that particular care needs to be taken when assessing the site conditions for any form of development.

Engineering properties (see also Appendix 4)

There are relatively few test results from these materials (Appendix 4), and those that exist from the Irish Sea Glaciolacustrine deposits may be skewed towards the properties of the clays, reflecting the flushing out of silts and sands during drilling. However, the general comments given above for cohesive soils (glaciolacustrine clays of pro-glacial Lake Teifi) apply to the clays within these interbedded deposits. Their low to high plasticity indicates a low to high shrinkage potential, and the presence of abundant silt laminae will result in highly anisotropic shear strengths and, particularly, low horizontal shear strengths. The occurrence of very low permeability clay beds at intervals throughout the sequence means that the silt and sand beds are likely to be water-bearing. Deeply buried silt and sand beds, sandwiched between clays, may contain groundwaters under artesian pressures.

Design consideration

i) Foundations

The low bearing capacities and high compressibilities of these mixed glaciolacustrine deposits present problems for foundations, as does the possibility of perched groundwater tables and water uplift pressures, and the likelihood of excessive total and differential settlements. Site investigations, often requiring closely-spaced boreholes, should attempt to determine the presence, depth and extent of soft compressible zones, the depth to sound strata, and nature of local ground water conditions.

Where limited thicknesses occur, wholesale removal and replacement of these materials with suitable fill may be an economic option, but alternative solutions may also be required, including piling and raft foundations. The techniques employed will vary, but are generally comparable to those for cohesive soils.

ii) Excavatability and stability of cut slopes and excavations

The clays are diggable, but immediate support is normally required to maintain the stability of trench sides and cut faces. Water inflow from overlying aquifers, and artesian ground waters escaping from breached, underlying aquifers should be anticipated. The effect of any excavation on the stability of adjacent slopes needs to be carefully assessed.

iii) Suitability as engineered fill

These mixed cohesive/non-cohesive deposits are generally unsuitable for use as fill. Soft, highly plastic parts of the deposit will be prone to large deformations by heavy plant. However, thick, well drained sand or gravel units exposed at surface may be suitable as local sources of granular fill.

6.2.2.4 SOFT/LOOSE SOILS

These comprise alluvium, older alluvium, alluvial fan deposits and tidal river deposits. They occur extensively along the main river valley and its tributaries. Tidal river deposits are confined to the estuary of the Afon Teifi, where they are gradational with salt marsh deposits (see organic soils) and, at their seaward limit, with shoreface and beach deposits (see non-cohesive soils); all these estuarine deposits are subject to diurnal flooding by brackish river waters. Older alluvium occurs at depth and has only been encountered in boreholes. All the alluvial deposits are extremely variable in composition, with cohesive, non-cohesive and organic materials being present as layers or lenses, one within the other. They include very soft to firm sandy, silty clays and silts, with impersistent peats and organic clays, and loose to dense, fine to coarse-grained sands and gravels with clay lenses. Some alluvial fan deposits may exhibit a higher proportion of gravel than the other alluvial deposits and will present ground conditions akin to those of non-cohesive soils (see below). Depths and thicknesses of these alluvial deposits vary considerably across the area. The alluvium of the Afon Teifi may exceed 3 m in thickness.

Engineering properties

In the near-surface zone the alluvial materials may become desiccated and stiffer, with a higher strength than softer underlying material. The silt/clay units within these deposits can generally be expected to be of low to intermediate plasticity and to exhibit medium to very high compressibilities, with high rates of consolidation settlement, particularly where soft organic clays and peats are present; tidal river deposits have given plasticity indices which suggest a low to medium/high shrinkage potential (Appendix 4). In general, however, the limited geotechnical data available for the various alluvial deposits fails adequately to represent the wide range of properties this group of materials will exhibit.

Design considerations

i) Foundations

Low bearing capacities, high compressibilities, high groundwater tables and water uplift pressures, and the likelihood of excessive total and differential settlements pose problems for foundations in these materials. Site investigations, often requiring closely-spaced boreholes, should establish the presence, depth and extent of soft compressible zones, and the depth to sound strata. Due to artificial straightening and natural changes in position of the river channels, abandoned meanders may occur at several locations in the alluvial floodplains of the main river and its tributaries. It is important that these features (which may contain soft, compressible organic clays and silts) are identified during site investigations prior to development and construction.

The techniques adopted for construction on these materials are comparable to those for glaciolacustrine deposits (both cohesive and mixed cohesive/non-cohesive types). The presence of dense gravels within the alluvial sequences may additionally allow the use of mini-piles for light to moderately-loaded structures, although heavy structures should be supported on piles founded on the basal alluvial gravels or bedrock. Groundwaters encountered in these various alluvial deposits may have a sufficiently high sulphate concentration to require measures to be taken to avoid attack on buried concrete (i.e. selection of appropriate sulphate-resisting cement in accordance with the BRE Digest 363 (Building Research Establishment,1991).

Tidal river deposits (in common with shoreface and beach deposits; see below), offer unusual ground conditions requiring specialist investigations and engineering.

ii) Excavatability and stability of cut slopes and excavations

Alluvial deposits are readily excavated using soft ground excavating machinery, but water inflow problems may be encountered. High groundwater levels mean that excavations in the alluvium are subject to severe water inflow, and immediate support is normally required to maintain the stability of trench sides and cut faces. Running sands may also be encountered below the water table.

iii) Suitability as engineered fill

Alluvial silts and clays, often with intercalated peat, and lacustrine deposits are generally unsuitable for use as fill. Alluvial sands and gravels may be suitable as 'granular soil' fill if care is taken in selection and excavation.

6.2.3 Non-cohesive soils

These comprise all glaciofluvial deposits, river terrace deposits, shoreface and beach deposits and blown sand. They predominantly consist of medium dense, fine- to coarse-grained sands and medium dense to dense, fine to medium gravels, with occasional cobbles and boulders (Plate 4). Impersistent layers and lenses of clays and silts are developed locally. Glaciofluvial ice-contact deposits, in particular, locally include substantial areas of poorly drained, till-like material. Glaciofluvial deposits are widely developed throughout the catchment, typically forming mounds, benches and terraces along the sides of the main valleys, but also occurring as isolated spreads on higher ground. River terrace deposits flank the alluvium of the Afon Teifi and its tributaries. blown sand deposits occur on both sides of the Teifi estuary and shoreface and beach deposits are present at the mouth of the river.

In terms of ground conditions, the shoreface and beach deposits are uncharacteristic of this group of deposits, as they experience diurnal flooding and saturation by sea water, and are also prone to flooding by brackish and fresh river waters during periods of high discharge. Detailed and specialist investigations should be carried out prior to any planned development on these deposits. The following generalisations, therefore, do not necessarily apply to shoreface and beach deposits.

Engineering properties

Apart from particle size grading curves for the Irish Sea fluvioglacial deposits, and some SPT values for glaciofluvial ice-contact and undifferentiated deposits of Welsh ice derivation (Appendix 4), there is little meaningful test data available for non-cohesive deposits.

Design considerations

i) Foundation conditions

The non-cohesive soils encountered at surface should provide good foundation conditions, although thicknesses and lithological variability should be confirmed during site investigation. Compressibilities are likely to be low to moderate in these deposits, which are generally well-drained, with water tables below the normal depth for shallow foundations. Perched water tables are unlikely, due to the impersistent development of clays, although the till-like inclusions in glaciofluvial ice-contact deposits may be an exception.

During ground investigations, checks should be made at specific sites to determine the sulphate content of groundwaters and, where appropriate, measures should be taken to protect attack on buried concrete.

ii) Excavatability and stability of cut slopes and excavations

Surface deposits are easily excavated by mechanical digging. Running conditions may be encountered in all the deposits of this group, both below and above the water table. This is a particular problem in blown sand, and is an acknowledged hazard in the glaciofluvial deposits of the Banc-y-Warren area [205 485], near Cardigan. Excavations and cut slopes will normally require immediate support. Casing will be required to prevent collapse of granular material into boreholes. In general, water ingress should not present problems unless borings or excavations extend below local stream or river levels, when hydraulic continuity may be anticipated.

iii) Suitability as engineered fill

Most glaciofluvial and river terrace deposits should be suitable for use as 'granular soil' (sand/gravel) fill, if care is taken in selection and excavation. Glaciofluvial ice-contact deposits are usually more variable in composition, and locally contain high proportions of clayey material, but may be suitable as a source of granular fill in places.

6.2.4 Organic soils

These comprise peat, lacustrine deposits, and salt marsh deposits. Organic soils include fibrous or amorphous peat or organic (peaty) silts and clays, which occur as irregular surface deposits, and as impersistent layers within the alluvium. Modern lacustrine (pond) deposits, which generally contain variable proportions of organic material, are also included in this category, as are the Rosehill salt marsh deposits of the upper Teifi estuary, east of Cardigan. The latter are intergradational with tidal river deposits and are similarly subject to diurnal flooding by brackish estuarine waters.

Engineering properties (see also Appendix 4)

Organic soils and peats give rise to soft ground conditions, and typically possess low densities, high moisture contents and low strengths. All peats suffer very high consolidation settlement on loading. The nature of organic soils is such that they are usually impersistent, or contain bodies of other materials of very different geotechnical properties; thus, differential settlements as well as total settlement may be a major problem. Settlements may also take place without external loading following either natural or artificially induced drainage and the lowering of local water tables. No geotechnical test results were available for organic soils in the project area.

Design considerations

i) Foundation conditions

Organic soils and peats offer very poor foundation conditions due to low bearing capacities and high, often uneven, settlements. The limited extent and relatively isolated nature of these materials means that they will not generally be encountered in most construction works. However, where they are present it is advisable that they are removed prior to development. The presence of soft peats or organic clays below normal foundation levels should be accommodated in foundation design. The groundwaters in organic soils and peats are commonly highly acidic, and appropriate precautions such as selection of suitably resistant concrete will normally be required to prevent damage and disintegration of buried foundations, culverts, and pipes (Building Research Establishment, 1991).

ii) Excavatability and stability of cut slopes and excavations

Excavation of organic soils and peats is easily accomplished by hand digging, although machine digging of alluvial peats and peaty clays is usually required when encountered at or below foundation levels. Very wet organic soils will offer poor face stability and, in extreme cases, may flow into the excavation; thus, immediate trench support and dewatering may be required. Dewatered organic soils may stand well without support.

iii) Use as engineered fill

Organic soils and peats are unsuitable under any circumstances for forming load-bearing fills (BS 6031: British Standards Institution, 1981a) due to their low strength, poor drainage characteristics and complex water-holding properties.

6.2.5 Landslips

The distribution of large areas of landslip are shown on Thematic Maps 1 and 4, and all known landslips are shown on Thematic Map 6. Detailed information on landslip locations are held in BGS files. Landslips occur throughout the project area, and their nature, formational processes and relevance to planning and development are discussed in the section of the report for Thematic Map 6. Salient points with regard to engineering ground conditions are summarised, briefly, below.

- Landslips vary widely in composition, from dominantly fine-grained cohesive materials to granular, non-cohesive material. They contain, or are bounded by, shear surfaces of low strength along which slip has commonly taken place.
- Landslips highlight areas of current or past instability and, wherever possible, development on these sites should be avoided. If this is not feasible, it is essential that the stability conditions of the slip and the surrounding land are established by site investigation prior to planned development and construction. The investigation of such ground is a specialist task and must be carried out in compliance with best current practice. Annex 1 to Planning Policy Guidance Note 14

(Department of the Environment, 1996) is of particular relevance.

- It is essential that the ground is made suitable by appropriate engineered remedial works, which should be undertaken by competent professionals, ensuring that the effect of any site development (e.g. construction loads, excavations and/or modification to the groundwater regime) on stability is accounted for in design.
- Landslip materials are often highly variable in composition and therefore generally unsuitable for use as engineered fill. The presence of wet zones associated with seeps and springs, hillslope locations, difficult access, the limited extent of many landslips and the risk of initiating further instability during excavation also make their use as a source of fill unviable.

6.2.6 Man-made (artificial) deposits

This includes made ground, worked ground, landscaped ground and disturbed ground. Although man-made deposits cover a very small part of the project area, they are concentrated in the vicinity of towns, where future development is likely to be focused. Thematic Maps 1 and 4 shows the location of only the largest areas of man-made deposits. These include sites where materials have been placed on the natural ground surface (made ground), areas of excavation for aggregate and clay which may be either partially or wholly backfilled (worked and disturbed ground) and areas, which have undergone extensive landscaping (landscaped ground). Smaller areas of made ground are shown on the 1:25 000 scale geology maps and details of these, and the location of additional, small sites of worked ground are held in BGS files. Man-made deposits are typically highly variable in composition, geotechnical properties and thickness (thicknesses of 1m to 2 m are common, but deposits over 20 m thick may occur in areas of old pits and railway embankments). Man-made deposits principally consist of bulk fill derived from excavations in superficial deposits and bedrock, but may also include variable amounts of domestic refuse and construction materials. Industrial slag from steel works in South Wales is known to have been used for some railway embankments. The settings in which man-made deposits occur include infilled valleys and gulleys, infilled low lying, marshy or soft ground which was prone to flooding, backfilled quarries and clay-pits, road and railway embankments, and areas of landscaping on large, modern housing and industrial estates. Only one licensed landfill site is present in the area at the time of writing (see Thematic Map 5).

In the largely rural setting of the Afon Teifi catchment, man-made deposits may be less of a problem than in areas with a long industrial and urban history. However, difficulties may still be encountered during the development of individual sites where such materials are present. Therefore, a knowledge of the engineering problems which can arise where man-made deposits occur is useful. A detailed assessment of ground conditions within individual areas of man-made deposits in the project area was not feasible, and therefore, the following section assesses features which relate to man-made deposits in general.

- In infilled valleys and made up levels of low marshy ground, man-made deposits may rest on soft alluvial clays, peat or head deposits, which may themselves undergo excessive differential consolidation settlement when loaded; this will be additional to consolidation of the fill itself. Therefore, the stability of the ground underlying the fill may need to be examined.
- If structures are built on piles passing through fill into underlying strata, negative skin friction on the pile, caused by settlement of the fill under its own weight, may be a major problem.
- In areas where the fill is deep, self-weight will often be the main cause of long-term settlement. With granular fills and poorly-compacted unsaturated fills, the major compression occurs almost immediately, and consequently most of the settlement due to self-weight occurs as the fill is placed. Nevertheless, significant further movements ('creep' settlement) may occur under conditions of *constant* effective stress and moisture content.
- Compression of fill by building loads will be very variable depending on the nature of the fill, its particle size distribution, compactness, the existing stress level, the stress increment and the moisture content. Movements which occur during building construction are likely to be much less of a problem than those which occur after completion of the structure. The long-term creep component is therefore of particular significance (see above).
- Loose, unsaturated fill materials are usually liable to collapse due to inundation with water. If this occurs after construction, a serious settlement problem may arise. It is believed that this is often a major cause of settlement problems in buildings on backfilled quarry sites. Problems can also be caused by water penetration into the fill through deep trench excavations for drains.
- Excessive differential settlements, leading to distortion and damage to buildings, can be expected in highly variable fill, or where the depth of fill changes rapidly. Where the deposits backfill a pit or quarry, they will invariably be less compacted than the surrounding ground, leading to differential settlement in foundations that straddle the edge of the filled area.
- On the sites of demolished buildings, load-bearing walls may be present at, or close to, the surface. Such sites may also contain basements, cellars, tunnels and service ducts which may be only partially filled with rubble and often remain as complete voids. New foundations which span these structures and the surrounding fill are liable to severe differential settlements.
- The problem of differential settlement may be compounded in cases where cavitation results from chemical or bacterial breakdown of the fill material.
- Fill comprising industrial waste may be potentially chemically active and capable of generating dangerous or combustible gases and toxic leachates.
- Domestic refuse in landfill sites will generate methane gas, which is highly combustible. The accumulation of methane in closed spaces in buildings, sub-floor spaces or basements may reach explosive concentrations (5 to 15% in air). Very old landfill sites may not contain material that will generate methane

6.3 ENGINEERING ROCKS (Solid Rocks)

The surface distribution of the various solid rock formations within the catchment is shown on Thematic Map 2, but for the purposes of their engineering properties they are grouped together. They are dominantly composed of cleaved mudstones (Plate 16), although beds of sandstone are common at some levels within the rock succession (Figure 5). Thick to very thick, well jointed sandstone beds are only common in the Moylgrove Group (Plate 11) and Cwmystwyth Grits Group, and are present as a minor component of the Yr Allt and Cwmere formations. Many of the thick sandstones in the Cwmystwyth Grits Group contain a high proportion of intercalated mudstone and are commonly cleaved. Thin sandstone beds occur in all the solid rock divisions, but are locally abundant in lower parts of the Nantmel Mudstones Formation and in the upper part of the Claerwen Group (Figure 5).

Distinctive, dark grey mudstones, rich in pyrite (iron sulphide), are a significant component in the Moylgrove Group, the higher parts of the Nantmel Mudstones Formation and the Cwmere Formation (Figure 5) (Plate 17).

Weathering

The engineering properties of the solid rocks are adversely affected by weathering. Weathering of the bedrock causes eventual breakdown and softening of the fresh material into an engineering soil, and the depth, and degree of weathering is of particular importance with regard to engineering ground conditions. The terminology used below follows Hawkins and Pinches (1992) and BS 5930 (British Standards Institution, 1981a) for the weathering of rock masses.

Weathering profiles in the rocks of the catchment vary greatly. They largely reflect site-specific factors such as the angle and direction of slope, depth of overburden, vegetation cover and groundwater movement. Profiles several metres in thickness are common, in which the complete spectrum of weathering features are developed. In such profiles unaltered, fresh bedrock passes upwards into a zone of rock with minor to extensive alteration along fracture surfaces (faintly to slightly weathered). This is succeeded by a zone in which the whole rock mass exhibits moderate to extensive alteration (moderately to highly weathered), followed by a zone of in situ, but completely altered rock fragments (completely weathered). Finally, there is a near surface zone of loose and reorientated, altered rock fragments which become finer in size upwards (residual soil). Well-developed weathering profiles may be capped by a top soil, but they are also overlain by glacial deposits in places, demonstrating that the profiles formed by weathering prior to the last glaciation of the region. In other areas, the products of ancient weathering have probably been removed by glacial scouring, and the natural bare rock surfaces exhibit only superficial, recent weathering. All gradations between these extremes of weathering are observed.

Weathering profiles are recorded from all the solid rock formations in the catchment and, in general, the composition of the bedrock appears to have little bearing on its susceptibility to weathering. Significant exceptions are the pyritic mudstones, where hydration of the pyrite during weathering, particularly along bedding and cleavage planes, leads to the rapid, deep-seated weakening and disintegration of the rock mass, and also accounts for the rusty and ochreous staining which characterises natural exposures of these rocks (Plate 17).

Geological faults

Geological faults are planes about which adjacent blocks of rock strata have moved relative to each other. Movement may have been vertical, horizontal or, more likely, a combination of the two. All the faults encountered within the project area are old fractures which formed millions of years ago and are no longer active. However, renewed movement along faults may occur during earth tremors or in response to major excavations and loading during construction. The faults usually consist of complex zones of sheared, fractured and disintegrated rock (gouge), rather than discrete slip planes, and these result in deep weathering profiles and varying bearing capacities within the fault zone. Lithologies with differing strengths and settlement characteristics may be juxtaposed on either side of a fault, and foundations straddling this contact can undergo differential settlements. This may not be a severe problem for light to moderately loaded structures, but foundations for heavy structures should be taken to a level where differential settlements are of an acceptable magnitude. Faults may also provide pathways for water, leachates and even gases. Site investigations should therefore aim to determine the presence and extent of faults prior to planned development and construction.

Plate 17 Deeply weathered, pyritic mudstones, Cwmere Formation.

Engineering properties (see also Appendix 4)

In an engineering sense, the term 'mudstone' is here used to describe the group of fine-grained sedimentary rocks that have a dominant grain-size in the clay or silt grades (<63 μm). They also include materials commonly known as siltstones, claystones and shales. The mudstones comprise moderately fissured, weak to moderately strong sedimentary rocks, whose general geotechnical characteristics are those of engineering rocks, but locally are intermediate with engineering soils. In addition to their particle size, an important feature of mudstones is their tendency to weaken when relieved of overburden pressure, due to the breakdown of interparticle bonds. Fresh mudstones are generally of low compressibility, but high consolidation settlements may be anticipated in weathered zones. They are locally susceptible to weathering, the end product of which can be a completely weathered, firm to stiff clay of low to medium, and locally high plasticity. Pronounced variation in the degree and depth of weathering is a major factor controlling the engineering behaviour of mudstones within individual sites.

Slight to moderate field permeabilities are not uncommon in mudstone sequences, but vary from place to place depending on the degree of weathering, as well as the amount of fracturing and the proportion of interbedded siltstones and sandstones. Waterlogging of the ground may occur locally where the mudstones are weathered to clay. The pyritic nature of mudstones in the Moylgrove Group is reflected in a total sulphate value of 0.14 (Appendix 4), the highest recorded within the catchment.

Fresh sandstones will be of low compressibility, although mud-rich varieties in the Cwmystwyth Grits Group will be gradational in behaviour with mudstones. The wide variation in SPT results from the solid rocks of the catchment probably reflects differences between sandstones and mudstones and their degree of weathering.

Design Considerations

i) Foundations

Provided the nature and depth of the weathered zone is properly assessed, the solid rocks should provide good foundation conditions. Because of the potentially wide range of rock conditions, it is sensible to use the results of in situ testing (e.g. plate loading tests) to assess the bearing capacity and settlement characteristics at particular sites. For shallow foundation levels in the weathered zone, allowable bearing pressures will be much lower than those on fresh or slightly weathered rock. Driven and cast in situ piles may be used to carry foundation loads through weathered material into fresh bedrock. Driven piles have disadvantages in that they tend to cause shattering, and may 'hold up' on sandstone layers underlain by severely weathered mudstone. Bored cast in situ piles are generally preferrable as they can readily penetrate the weathered zone, whose characteristics can be inspected. Site investigations should be sufficiently detailed to give adequate knowledge of the rocks below the toes of piles. Pile loading tests should be carried out prior to the main work to confirm chosen loadings and penetrations.

When exposed to wet conditions, some mudstones may lose strength and deteriorate to clays. Mudstones with a high pyrite content appear to be most susceptible to this process, which may result in a marked reduction of bearing capacity and loss of side friction for piles. For major excavations, it is advisable to carry out slaking tests on the mudstone lithologies to assess the likely degree and rate of deterioration and, where appropriate, employ measures to prevent water ingress. Groundwater, particularly in the vicinity of the pyritic mudstones, may have a sufficiently high sulphate concentration that special measures are required to avoid corrosion of concrete.

Fault-zones may present problems of low bearing capacity and excessive differential settlements, and site investigations should attempt to determine these zones as accurately as possible prior to foundation design.

ii) Excavatability and stability of cut slopes and excavations

Weathered mudstones can be readily excavated by mechanical scraping or digging, but ripping or pneumatic breakers and even blasting may be required for fresher, more indurated mudstones in deep excavations. Excavation methods in thick bedded sandstones will depend on the degree of weathering, joint and bedding spacing, and local variations in intact rock strength. Highly weathered sandstone may be excavated by mechanical digging, whereas fresh or slightly weathered rock may require ripping or pneumatic tools for excavation. Blasting may be needed for major excavations in massive sandstone.

Temporary excavations in fresh to moderately weathered mudstones should be stable in the short to medium term but slumping may occur in highly weathered zones. Cut faces in massive to moderately-jointed, unweathered sandstone may remain stable at steep angles in the long term, but weathered zones, mudstone interbeds and perched water tables can considerably reduce stability. Water seepages may occur from siltstone and sandstone beds and accelerate deterioration of cut faces; rain and heavy construction traffic may exacerbate this process. In some cases, temporary cut slopes may need protection (e.g. by covering with plastic sheeting or tarpaulins). Excavated slopes in fault zones may require immediate support due to the presence of shattered rock and clay gouge of low shear strength.

iii) Suitability as engineered fill

Highly weathered mudstones are generally classified as 'cohesive soil' for earthwork compaction purposes and fresh to slightly weathered material as 'dry cohesive'. Many of the mudstones may be successfully used as embankment fill, but the material should be placed as soon as possible after excavation and subjected to minimum construction traffic when wet. Pyritic material in mudstone lithologies may slowly oxidise on exposure to generate sulphate in acid conditions, requiring the selection of suitably resistant cement for buried concrete structures in engineered mudrock fill.

Sound sandstone rock may be suitable as rock fill if care is taken in selection and excavation. However, use as a high grade fill may be limited by the occurrence of intercalated mudstone beds and the variable amount of clay and silt-size particles which cement many of the sandstones. For compaction purposes, sandstones are generally classed as a graded granular soil.

6.4 SUMMARY AND RECOMMENDATIONS

Over most of the area, ground conditions should present no major problem to engineering development, provided that adequate information is obtained to confirm the engineering characteristics of specific sites. This should involve reference to existing information (e.g. geological maps, borehole records and existing site investigation reports) during desk studies, followed by a properly focused site investigation at the feasibility and design stages of a planned development project.

A variety of general problems may be encountered during development and construction in the area, although virtually all could be overcome by modern engineering methods, at varying cost. The most significant, particularly with respect to foundation conditions, are:

- variability of natural superficial deposits
- weathering of solid rocks
- landslips

Variability of natural superficial deposits

Site investigations in the natural superficial deposits should aim to establish their thickness (i.e. the depth to bedrock), and their lithological and geotechnical variability as accurately as possible. Rapid lateral and vertical changes may make this task difficult without closely-spaced boreholes or trial pits, even on small sites. On larger sites, a multidisciplinary approach for ground investigations is suggested. Geophysical methods, for example, in conjunction with boreholes and trial pits can be of particular help in determining the nature of the drift deposits and depth to bedrock, particularly in deep buried channels. Combined resistivity, gravity and cross-hole seismic tomography surveys are a particularly powerful tool for assessing the dimensions of buried channels and nature of the infill. In addition to boreholes, static cone penetration testing (CPT) may be used. CPT's (sometimes known as 'Dutch cone' soundings) can provide a rapid means of obtaining continuous profiles of soil stratification by measuring cone resistance and side friction for standard rates of penetration.

Weathering of solid rocks

Weathering of bedrock is an important factor affecting engineering ground conditions in the catchment, particularly the degree and depth of weathering associated with fault zones and pyritic mudstones. Site investigations should therefore aim to determine the extent of weathered profiles prior to planned development. The contrast between fresh, intact bedrock and fragmented, weakened and wetter materials of the weathered zones may allow the use of geophysical methods (e.g. electrical resistivity and electromagnetic techniques). These techniques can greatly assist in the optimum siting of boreholes and pits, especially where shallow surface weathering of bedrock grades laterally into the deeper weathered profiles of fault zones.

Landslips

Landslips are commonly developed on moderate to steep slopes throughout the catchment, particularly in areas underlain by cohesive glaciolacustrine clays (see Thematic Map 6). It is essential that these areas are recognised, and the stability conditions of the immediate site and the adjacent slopes are established by site investigation prior to any development. Wherever possible, development on landslip should be avoided, but if this is not feasible then it is essential that the ground is made stable by appropriate engineered remedial works. This is a specialist task and, where necessary, engineered remedial measures to enhance stability should be undertaken by competent professionals, ensuring that the effect of any site development on stability is accounted for in design. Recommendations for site investigation techniques and appropriate remedial measures in areas of landslipped ground are given in the section of this report, which assesses Thematic Map 6.

7 Hydrogeology and flood limits — Thematic Map 5

Hydrogeology is the study of just one mineral, water. It is specifically concerned with assessing the properties of underground water (groundwater) and of water-bearing rocks or sediments known as aquifers. This includes the assessment of groundwater recharge and discharge rates, the volumes of groundwater available in storage, and patterns of groundwater movement. It is also concerned with groundwater quality, which is derived from chemical interaction between the water and the rocks and/or sediment it is stored within and passes through. Such an understanding of groundwater occurrence, movement and composition, and of aquifer geometry and permeability is essential for the development of regional planning policies which are in harmony with national water conservation and protection strategies.

The solid and drift geological maps (Maps 1 and 2) form the basis for understanding the hydrogeology of the catchment and have permitted the principal aquifer units to be identified. Map 5 depicts the outcrops of these aquifer units within the catchment.

As a result of the Environment Agency's interest in the hydrogeology of the catchment, they provided additional funding for more detailed work. This entailed the production of a borehole and well inventory and an intensive field-based programme of groundwater measurements, sampling and analysis undertaken at selected sites in the catchment. These results are summarised below, with a more comprehesive account provided in a separate report compiled for the Environment Agency.

Little was known about the detailed hydrogeology of the mid-Wales region beforehand. Indeed, it was believed that the hydraulics of the granular drift deposits of the Teifi valley would form the main aquifer, and that the underlying solid rocks would be weakly permeable; a situation which has long been recognised in similar Lower Palaeozoic terrain in both southern Scotland and Northern Ireland (Robins, 1995). The project has shown this not to be the case in mid-Wales, and has identified the bedrock as the main producing aquifer, supported by groundwater storage in certain categories of the drift deposits.

A separate, but allied aspect of the study identifies areas of the catchment in which river flooding has been, or may become a potential problem; another factor to be considered in planning and development.

7.1 WATER SUPPLY

Mains water throughout the catchment is provided by Dŵr Cymru (Welsh Water) and is derived principally from surface sources which supply local reservoirs. Dŵr Cymru augment these local supplies with water obtained from the Olwen Borehole [5817 4959], north of Lampeter, and by licensed abstraction directly from the Afon Teifi at Llechryd [2280 4350]. In addition, Map 5 also shows the location of a further nine licensed boreholes or wells, which occur within or adjacent to the surveyed part of the catchment, and of over 20 other boreholes and wells which are not licensed. Many farms have recently had boreholes drilled in an effort to reduce their dependence on relatively expensive mains supply. The map also plots the position of many of the springs and old wells within the catchment.

7.2 AQUIFERS

Map 5 shows the surface distribution of potential aquifer units within the catchment. Although the presence of springs and wells demonstrates that many of the areas distinguished as moderately permeable aquifers on Map 5 are groundwater bearing (see below), the map should not be taken to imply that groundwater is universally available in useable quantities at any particular site within these areas. Specialist investigations are required to determine the presence, extractable volume and quality of groundwater at any site.

All the aquifers within the catchment are classed as moderately permeable. In terms of the Environment Agency classification of aquifers (National Rivers Authority, 1992), a moderately permeable aquifer equates with the category 'minor aquifer'. Minor aquifers comprise 'fractured or potentially fractured rocks which do not have a high primary permeability, or other formations [including drift deposits] of variable permeability. Although these aquifers will seldom produce large quantities of water for abstraction, they are important both for local supplies and in supplying baseflow for rivers. In certain local circumstances minor aquifers can be highly vulnerable to pollution'.

Two types of moderately permeable aquifer are present: 1) solid; and 2) drift.

7.2.1 Moderately permeable solid aquifers

All the solid rocks in the region have potential as moderately permeable aquifers and many of the recently drilled water boreholes are sited, either wholly, or partly in solid rock. The various sedimentary lithologies which make up the rock succession are, when fresh, typically well cemented and highly indurated, and preserve little of their primary porosity. Their aquifer potential however, stems from the presence of numerous small scale cracks and fractures throughout the rock mass, a property termed fracture porosity. Such fracturing relates to the pervasive buckling, faulting and cleavage suffered by these rocks during ancient earth movements, and appears to be largely unrelated to their primary lithology. Thus sandstone and mudstone dominated divisions appear to offer similar aquifer potential and have therefore not been distinguished on Map 5. The degree of fracture porosity in the rocks of the catchment may vary. It is likely to be greatest in the near surface zones, especially in the vicinity of faults and particularly in weathered zones. However, current water borehole practice in the region appears to favour deep drilling so that the bore acts as a sump for groundwater derived from both surficial drift and weathered layers, as well as from deeper, fracture-related sources of water ingress.

7.2.2 Moderately permeable drift aquifers

The drift deposits of the catchment, which have aquifer potential, are those which contain a high proportion of clast supported, granular materials and preserve a high level of primary intergranular porosity, principally sands and gravels. However, as many of these moderately permeable drift aquifers contain scattered beds and lenses of less permeable (clayey) materials, the permeability is variable in both a vertical and horizontal direction. Map 5 shows the distribution of the various groupings of drift aquifer materials as they occur at the surface, namely (i) glaciofluvial and heterogeneous glacial deposits, head, head gravel and blown sand, (ii) alluvium, (iii) river terrace deposits, (iv) major alluvial fan deposits and (v) estuarine deposits. However, both low permeability drift (non-aquifer) and other aquifer drift deposits may intervene at depth between these surface materials and solid rock (see Map 1). The map therefore should not be taken to imply that, within the areas delineated as drift aquifer, these surface materials are necessarily present in sufficient thickness to support useable groundwater abstraction.

The most widespread group of drift deposits forming moderately permeable aquifers comprises glaciofluvial and heterogeneous glacial deposits, head and head gravel, and blown sand (see also Map 1). This group of materials occurs throughout the catchment and is potentially the most significant of the drift aquifers. It is particularly widespread, and at its thickest, in the western reaches of the project area notably around Penparc [210 480], Ferwig [185 497] and west of St Dogmaels; and, in the east, within the main Teifi valley between Llanfihangel-ar-arth [456 398] and Lampeter. Extensive spreads also occur in the upper reaches of the Ceri valley, around Rhydlewis [347 474]. In these areas, these aquifers are known to locally exceed 50 m in thickness, but major lateral changes in thickness are common. The drift materials in this group commonly contain subordinate beds and irregular masses of clay-rich, low permeability materials. The presence of such impervious layers may seriously affect the local movement and extractability of groundwaters at particular sites and underlines the need for site specific investigations.

The various types of alluvial deposit (estuarine deposits, alluvium, river terrace deposits and major alluvial fan deposits) that form drift aquifers in the catchment are each distinguished separately on Map 5 because of their significance in terms of flood susceptibility and prediction (see below). The various estuarine deposits (tidal river, salt marsh, marine shoreface and beach deposits), which occupy the tidal reaches of the Afon Teifi, have been grouped together as a brackish aquifer.

The most widespread and thickest developments of these various alluvial aquifers are those associated with the modern courses of the Afon Teifi and its largest tributaries, including the Afon Cych, Afon Ceri, Afon Tyweli, Nant Cledlyn and Afon Grannell. However, in contrast with other river systems in the region, such as the Afon Rheidol, the alluvial sequences of the Afon Teifi and its tributaries appear to be quite thin. The highest river terraces may be underlain by several metres of gravel-dominated material (see Map 1), but in many areas the modern floodplains of the catchment may be underlain by alluvial deposits more or less equal in thickness to the bank height of the present river or its tributaries. These attenuated alluvial sequences reflect the net prevalence, since late glacial times, of downcutting over deposition throughout the surveyed part of this river system. Moreover, thick sequences of clay-rich, glacial materials with little aquifer potential, including tills and glaciolaccustrine deposits, are believed to underlie many of the modern alluvial belts of the valley (see Map 1), further limiting their potential as sites for groundwater abstraction.

7.3 LOW PERMEABILITY DEPOSITS (NON-AQUIFERS)

These are shown on Map 5 as a single group of materials and typically comprise clay-rich materials, principally including the several categories of till and glaciolacustrine deposits (see Map 1). The distribution of low permeability drift has an important bearing on the movement of groundwaters into and within, adjacent solid and drift aquifers, for low permeability drift deposits commonly underlie or pass laterally into surface drift aquifers. The map also shows those areas in which moderately permeable drift aquifers and low permeability drift deposits occur in intimate association, localities where vertical and lateral groundwater movement may be restricted.

7.4 ARTIFICIAL DEPOSITS AND WORKED GROUND

Areas of the catchment distinguished on Map 1 as made ground, landscaped ground, disturbed ground and worked ground are shown as a single category on Map 5. These represent areas where there has been substantial human interference with the original land surface. The natural surface drainage and groundwater movement patterns may have been disrupted or destroyed and, as a consequence, the properties of any contiguous or underlying aquifer may have been adversely affected. In particular, these are regions where there is a high likelihood of waste materials being present and these carry a risk of contamination to any surface and groundwaters which pass through them.

7.5 SPRINGS AND WELLS

Map 5 shows the distribution of the many springs and old wells, which occur throughout the surveyed portion of the catchment. Most of the locations are taken from the Ordnance Survey 1:25 000 scale maps for the region, but also included are additional sites identified during field surveying. Many of these wells and springs have been used as local sources of water, and some are still in use. Springs occur along the line at which the watertable intersects the ground surface. Visits to a number of the sites labelled as wells on the Ordnance Survey maps showed that many of these were in fact collecting tanks at springs.

The map shows that the springs occur in three principal settings: i) within outcrops of solid rocks; ii) at solid/drift contacts; iii) within outcrops of drift aquifer, including many that are at or close to contacts between drift aquifers and low permeability drift deposits.

The majority of the plotted spring and well sites fall within areas where solid rock crops out at surface or, as is more common, where it lies below a shallow cover, typically less than 2 m thick, of soil and regolith. Flows of up to 5 $l\ s^{-1}$ have been recorded, though flows of $<1\ l\ s^{-1}$ are more typical.

There are many springs and wells that are located at, or close to, the mapped contacts between the solid rocks and drift deposits. These occur both where drift deposits lie down gradient of areas of solid outcrop and where drift deposits are sited up gradient of solid rocks. Many of these contact springs are associated with low permeability drift/solid contacts, rather than drift/solid aquifer contacts, reflecting the measure of hydraulic continuity between the solid and drift aquifers.

Most of the remaining springs and wells lie within areas where drift aquifers immediately underlie a superficial soil cover and most of these are located at, or close to, contacts with low permeability drift deposits.

7.6 GROUNDWATER POTENTIAL

The average sustainable yield of a 40 m-deep, 100 mm diameter borehole in the solid aquifer is 0.3 $l\ s^{-1}$. Spring discharges are typically 0.6 $l\ s^{-1}$ and range up to 3 $l\ s^{-1}$. Although there are few abstractions directly from the drift aquifer, the public supply source at Olwen [SN 582 496] is licensed to abstract 395 $m^3\ d^{-1}$ from glaciofluvial sand and gravel deposits. The borehole is 27 m deep. Total current groundwater use in the catchment is estimated at some 2000 $m^3\ d^1$ (Figure 7).

	Estimated use	Number	Total abstraction
Domestic - single property	0.6	809	485
Domestic>25 people	1.2	83	100
Farm	1.5	68	102
Farm dairy	6.5	132	858
Commercial	8	20	160
Public supply	377	1	377
Total		1113	2082

Figure 7 Groundwater consumption ($m^3\ d^{-1}$) in the Afon Teifi catchment.

Mean river flow of the Afon Teifi at Glan Teifi [2440 4160] is 2.5 $Mm^3\ d^{-1}$, well over one thousand times greater, than current groundwater use. The available groundwater resources undoubtedly could be developed further without detriment to river flow, but it is likely that the main inhibiting factor to groundwater development is the layered nature of the drift deposits and the low fracture permeability of the solid aquifer.

7.7 GROUNDWATER CHEMISTRY

Samples were collected from 19 boreholes, 27 springs and 6 wells and from the Afon Teifi at Cenarth. The major element chemistry of the groundwaters analysed as part of the study ranges from calcium-bicarbonate type to calcium-chloride type (Figure 8). Calcium bicarbonate waters reflect significant interaction with calcium carbonate, whereas calcium chloride waters reflect a shorter residence time or where carbonate minerals are not present in significant quantities. The groundwater is weakly to moderately mineralised, and pH ranges from 5.2 to 7.6. Most major element concentrations are below the European Community Maximum Admissible Concentration (MAC), although potassium exceeds the MAC in some samples, whereas nitrate approaches the MAC concentration in only a few samples. Iron and manganese are generally low, reflecting the presence of oxygen in the waters, and silicon concentrations are variable. It should be noted that neither analysis of bacterial populations, nor a comprehensive analysis of organic species was undertaken and that most of the groundwaters are potable, only with regard to their inorganic content.

There are three influences on the inorganic chemistry: marine, anthropogenic and geological. The marine influence causes an increase in sodium and chloride ion concentrations towards the western end of the catchment due to the action of sea spray and salt deposition. Anthropogenic influences (i.e. related to human activities) are evident at isolated sites inland where some boreholes near farm buildings and low-flow springs used by livestock have provided samples with enhanced total organic carbon, nitrate, potassium and chloride. These enhanced concentrations derive from the application of sludge to land and the use of fertilizers. In addition, boreholes drilled through made ground and in urban areas may show enhanced concentations of trace metals and high Na and Cl due to road salting.

The geological influence is greatest where the bedrock contains a high percentage of reactive minerals (e.g. calcium carbonate, ferromagnesian minerals in igneous rocks, strontium minerals) and wherever older groundwater, which has had the most opportunity for reaction due to increased residence time is present. The influence of primary lithology on groundwater chemistry in the solid aquifer is important. The presence of mudstones containing pyrite (iron sulphide) throughout the Moylgrove Group and Cwmere Formation, and in parts of the Nantmel Mudstones Formation and Claerwen Group (see Map 2, Figure 5), is reflected in higher sulphate levels in groundwaters derived from these strata, as most sulphate comes from the oxidation of sulphide.

The effects of drift deposits on the chemistry of groundwaters in the UK is often difficult to establish, principally because the drift deposits are of local origin and chemical reactions are generally similar to those occuring in the groundwater in the bedrock. This study affords a good opportunity to assess differences in groundwater chemistry imposed by drift deposits, as those deposited by the Irish Sea ice in the west of the catchment contains abundant exotic material, while those deposited by the Welsh ice sheet in the east, largely comprise local materials. A north-south line through Llangela broadly defines the eastern limit of the deposits of the Irish Sea ice. The solid geology of the catchment is dominated by Ordovician and Silurian mudstones, siltstones and sandstones which are generally base poor and slow to weather. In contrast, the deposits of the Irish Sea ice contain materials that weather more easlily, such as shells, limestones and basic igneous rocks.

The groundwaters of the catchment show pronounced regional variations in chemistry, although there is some overlap in concentrations. In the western part of the catchment, the concentration of several major and trace elements in some groundwaters are relatively high with the highest concentrations, largely coincident with the area covered by the deposits of the Irish Sea ice. This is particularly clear for Ca and Sr, which are strongly influenced by geological controls, in this case the abundance of shell material and limestone in the deposits of the Irish Sea ice. Other elements that show enhanced concentrations in the western part of the catchment include Na, Mg, HCO_3, Si and to a lesser degree Li, F and U. Conductivity and pH are also higher in the west. The

	CEC[1]		WHO[2]	Boreholes	Springs	Wells	Afon Teifi	Detection Limit
	GL[3]	MAC[4]	GL[3]					
mg l^{-1}				N = 19	N = 27	N = 6	N = 2	
Ca	100	-	-	13 - 66	7 - 83	15 - 54	11	0.02
Mg	30	50	-	3 - 16	2 - 18	3 - 14	3	0.04
Na	20	150	200	10 - 52	5 - 35	6 - 18	9	0.02
K	10	12	-	0.5 - 17	0.4 - 34	0.6 - 9	1.6 - 1.7	0.3
Cl	25	-	250	14 - 92	11 - 63	12 - 43	13 - 16	0.2
SO_4	25	250	400	6 - 41	6 - 28	4 - 18	9 - 10	0.3
Al	0.05	0.5	0.2	0.003 - 0.19	0.001 - 0.31	0.003 - 0.032	0.026 - 0.044	0.0008
NO_3-N	25	50	45	< 0.4 - 32	< 0.4 - 19	0.9 - 41	< 0.4	0.4
Fe	0.05	0.2	0.3	< 0.006-0.48	< 0.006-0.72	0.006 - 0.017	0.014-0.071	0.006
Mn	0.02	0.05	0.1	< 0.001-0.217	< 0.001-2.4	0.001-0.013	< 0.001-0.016	0.001
µg l^{-1}								
Cu	3000	-	1000	0.5 - 676	< 0.3 - 17	0.6 - 31	1.3 - 1.5	0.3
Zn	5000	-	5000	1 - 198	1 - 62	2 - 19	6 - 9	1
F		1500	1500	50 - 230	30 - 160	50 - 70	50	10
Ba	100	-	-	1 - 161	0.8 - 40	2 - 25	5.4 - 5.6	0.3
Ag	-	10	-	< 0.06	< 0.06	< 0.06	<0.06	0.06
As	-	50	50	0.4 - 2	< 0.3 - 2.9	0.4 - 6.5	0.7 - 0.8	0.3
Cd	-	5	5	< 0.04 - 0.05	< 0.04 - 0.17	< 0.04 - 0.05	< 0.04 - 0.05	0.04
Cr	-	50	50	< 0.8	< 0.8 - 1.9	< 0.8	< 0.8	0.8
Ni	-	50	-	< 0.8 - 11	< 0.8 - 6.7	< 0.8 - 3	1	0.8
Pb	-	50	50	< 0.4 - 3.6	< 0.4 - 5	< 0.4 - 3.5	< 0.4	0.4
Sb	-	10	-	< 0.1 - 0.4	< 0.1 - 0.2	< 0.1 - 1.6	< 0.1	0.1

Figure 8 World guideline values for selected inorganic constituents of waters and ranges of waters analysed as part of this study. [1]Council of the European Communities Directive 80/778; [2]World Health Organisation, Guidelines for Drinking Water Quality, 1984; [3]Guide level; [4]Maximum admissable concentration.

groundwaters of the eastern part of the catchment are considered to represent background concentrations for the Lower Palaeozoic rocks and the drift, and it is evident that these background values have been significantly modified in some of the groundwaters from the west of the catchment due to contact with the deposits of the Irish Sea ice sheet.

7.8 GROUNDWATER VULNERABILITY

In general, groundwater obtained from both solid and drift aquifers is normally of high quality, requiring little treatment prior to use. However, it is vulnerable to contamination from both diffuse and point-sourced pollutants, from both direct discharges into groundwater and indirect discharges into or onto land. Since the decontamination of groundwater is commonly difficult, prolonged and expensive, the prevention of pollution is of great importance. **The need to protect groundwaters from surface pollutants should be considered as a general planning requirement in all development proposals.**

The Environment Agency's Policy and Practice for the Protection of Groundwater (National Rivers Authority, 1992) has provided a framework for the protection of both individual groundwater sources and aquifers. Groundwater Vulnerability maps at 1:100 000-scale now cover all of England and Wales. The Afon Teifi catchment is covered by parts of Sheet 34 (Pembroke) (Environment Agency, 1997) and Sheet 27 (Carmarthen) (Environment Agency, in press) of this series. These depict the moderately permeable drift aqiifers as moderately vulnerable to pollution and the solid aquifer as weakly vulnerable to pollution. In reality, it is likely that both are equally vulnerable to surface pollution entering the groundwater body. This is because the groundwater body is shallow and relatively unprotected in both drift and solid aquifers, and they both contain higher permeability pathways for the rapid transport of egressing contaminants.

As a general planning rule, care is needed to protect groundwater in the catchment from surface pollutants. Activities that pose a hazard of pollution should be undertaken with caution and appropriate measures taken to minimise risk. Such activities include sewage sludge disposal to land, storage and use of road salt, landfill, soakaways, the storage, handling and disposal of chemicals, fuel storage, etc.

7.9 FLOOD LIMITS

Map 5 provides an indication of those areas of the catchment which are, or which in the recent past, have been susceptible to regular river flooding, by depicting the active, or recently active flood plains of the Afon Teifi and its tributaries. It also shows the tidal reaches of the modern river which are prone to at least partial flooding on a daily basis. The limits of these flood plains and tidal reaches are based on the distribution of the various river and tidal flood deposits (e.g. alluvium, tidal river deposits, etc.). Though the mapped outer boundaries of these materials are likely to broadly coincide with the upper or outer limits of regular river or tidal flooding, anomalously large flood events may affect areas significantly outside those indicated. Map 5 also shows those areas of the Teifi Valley (excluding the tributary valleys and the estuary) that the Environment Agency, at the time of writing, regard at risk of flooding and to which flood warnings refer. **Neither the BGS nor the Environment Agency data include information relating to localised flooding from drains and watercourses.**

However, the map does not show those flood-susceptible areas of the catchment in which alluvial deposits are either: i) not present; or ii) where their former surface is obscured by artificial deposits (made ground) and/or has been disrupted by excavation and remodelling (worked ground and landscaped ground). An example of the former is provided by the rock gorges of the Afon Teifi. Though these are acknowledged as sites of regular flooding, the violent nature of the floods within these constricted reaches of the river rarely allows flood deposits to be preserved. Of greater importance however, is the omission of those areas in and around the main towns of the catchment, where made or landscaped ground obscures the floodplains of the Afon Teifi and its tributaries. In many instances these materials have been used to elevate the existing ground surface above the level of regular flooding, thereby creating land suitable for development. Examples of this include Lampeter, where the floodplain of the Afon Dulas is largely covered by landscaped ground, and Llanybydder where a substantial section of the floodplain of the Afon Teifi has been covered by made ground.

It should be noted however, that in some circumstances the presence of made ground on the narrow flood plains of tributaries may exacerbate flooding rather than preventing it. A case in point is the lower course of the Afon Mwldan in Cardigan. There, this river flows either through culverts or in a deep trench flanked by a considerable thickness of made ground overlying the former floodplain. Though these arrangements cope with normal flood discharges and have allowed the area to be developed, abnormal flood events, such as occurred in 1875 and 1993, have resulted in substantial flooding. Accordingly, Map 5 should not be relied up on as an indicator of flood susceptibility in such areas. Development in the vicinity of any water course associated with areas of made or landscaped ground within the main towns, particularly where these water courses are entrenched or culveted, requires specialist investigations to assess flood risk.

The following assessment of the flood susceptible land types shown on Map 5 is based on gross geological, geomorphological and topographical criteria only. No account is taken of flood protection measures which are already in place or which are planned, and which may mitigate the risk or frequency of flooding at particular sites within the areas shown. This account is intended to provide only a general guide to flood susceptibility and should not be used as a substitute for site specific flood risk assessments, for which the most up to date Environment Agency data should be consulted.

7.9.1 Tidal estuary of the Afon Teifi

The tidal part of the Afon Teifi extends from Poppit Sands at the coast, inland as far as the Cilgerran gorge [180 450] Plate 3. The area depicted on Map 5 as estuarine deposits encloses those areas underlain by tidal river deposits, salt marsh deposits and marine beach and shoreface deposits, all of which form areas of flat to gently sloping ground flanking both sides of the river.

These estuarine settings are normally subject to at least partial flooding twice a day in response to every rising tide. The daily level of inundation reflects variations in both tidal and weather conditions. At the coast, the tidal range (between high and low water) varies from a maximum of about +5.4 m AOD, during spring tides, to a minimum of about +1.4 m AOD at times of neap tides with correspondingly greater or lesser amounts of the estuary prone to flooding. However, daily weather patterns can dramatically alter the level of inundation predicted from local tide charts. Onshore winds can ensure that low-water remains substantially elevated above its predicted level. More significantly, the combination of strong onshore winds with both low atmospheric pressures and spring tides can lead to exceptionally high tides. Should these conditions coincide with periods of high river discharge, the combined river and tidal flood waters could inundate areas well beyond the estuarine reaches shown on Map 5.

7.9.2 Present day floodplains of the Afon Teifi and its tributaries

Upstream of the estuary, the lowest tracts of flat ground, which flank the Afon Teifi and its tributaries, represent their active floodplains and coincide with the mapped limits of their Alluvium (Map 5) (Plate 18). They represent those portions of the alluvial belts of the catchment which are **most** susceptible to regular river flooding, with flooding most likely to occur during the winter months at times of high precipitation or following the rapid thaw of an extensive snow cover (Plate 19).

In western and central parts of the project area, the active floodplain of the Afon Teifi is defined by a belt, rarely greater than 400 m wide, across which the river meanders from side to side. However, in the east, between Pencarreg [535 452]and Lampeter, the active floodplain of the Teifi expands locally to more than a kilometre wide. Much of this broad stretch of floodplain was submerged during the 1987 flood of the upper Teifi valley. Tributary floodplains seldom exceed 200 m in width and are normally much narrower.

Improved land drainage, both in the forested upland parts of the catchment and in the cultivated lower levels, facilitate the more rapid transfer of rainwater to the river system than in previous times, and may promote more frequent, but shorter lived flood events than previously experienced. Long term variations in regional precipitation levels consequent to predicted climatic changes (global warming, etc.) will also impact on the frequency of river flooding within the Teifi catchment.

7.9.3 River terraces representing former floodplain levels of the Afon Teifi and its tributaries

These comprise flat-topped benches in the valley bottom occuring at levels somewhat higher than the modern floodplains of the Teifi and its tributaries. They represent the remnants of earlier, higher floodplain surfaces still preserved within the alluvial tracts of the catchment. Up to three terrace levels (first, second and third), sited at progressively greater elevations above the modern water courses and their floodplains, can occur in any one area. Though abandoned as sites of regular river flooding, these terrace surfaces are still liable to inundation during major flood events (see below). Self evidently, their levels of

Plate 18 Flood plain of the Afon Teifi at Llechryd [2185 4368], (note the line of debris left by flood waters).

susceptibility to flooding are determined by their height. The lowest (or first) terraces are remnants of the most recently abandoned former floodplain surface. Reports that these terraces have been flooded within the lifetime of many farmers are widespread (e.g. during the 1987 flood). The highest (or third) terraces are remnants of the oldest floodplain surface still preserved within the catchment; a floodplain which was probably last regularly flooded soon after the retreat of glaciers from the catchment, some 10 000 years ago. These highest terraces are now only likely to be flooded during truly exceptional and highly infrequent events. The middle (or second) terraces have an intermediate susceptibility to flooding.

7.9.4 Major alluvial fans

Also shown on Map 5 are the deposits of some of the larger alluvial fans present within the catchment. The susceptibility of these fan surfaces to flooding, and the style and duration of flooding which affects them, may vary according to fan geometry and gradient. Large, very gently sloping fan surfaces, developed where some of the larger, primary tributaries of the Teifi join the main river valley, as in Llanybydder and around Lampeter, typically grade into both the main river floodplain and the floodplains of their parent tributaries developed upstream. They therefore have the same, relatively high susceptibility to regular and prolonged flooding as these contiguous alluvial tracts. The smaller, but typically steeper, fans developed at the confluences of secondary, normally higher gradient tributaries of the catchment, may be prone to flood with the same frequency as their relatives associated with main river, but their steeper gradients and reduced catchment are likely to ensure that both the depth and duration of flooding on these fans will be less.

7.9.5 Current Environment Agency Flood Warning Area

Map 5 shows the areas in the main Teifi valley, which, at the time of writing, are considered at risk of flooding according to Enviroment Agency (Wales) Local Flood Warning Plan for the Dyfed Powys Police Force area. Although the flood risk areas are subdivided into a series of zones (A, B, C etc.) on the maps included in this plan, the zones are not shown on Map 5. The zones reflect the variation in the risk of flooding with river conditions of differing severity, the latter designated by different levels of issued flood warning, i.e Flood Watch, Flood Warning and Severe Flood Warning. For example, Zone A areas are most prone to flooding and will be at risk of inundation even when Flood Watches are issued; when Flood Warnings are issued both Zone A and Zone B areas may be at risk; and when severe Flood Warnings are issued, all the zones may be liable to severe flooding. **Anyone requiring detailed information on the current Environment Agency flood zonation, the procedures and significance of the flood warnings the Agency issues, or on the limitations attached to the Agency data for any sector of the Afon Teifi should consult the Dyfed Powys Police Area Local Flood Warning Plan. One section within this plan, which is available for inspection at the local Environment Agency Area Office, contains information for the Teifi Valley.**

The Environment Agency information is based on their current records of flooding of the Afon Teifi up to March 1997, and does not include data relating to its major tributaries or to localised flooding from drains and watercourses. The Environment Agency data should not be taken as definitive, as full surveys may not have been carried out. Further information should be obtained from the Environment Agency (Wales).

It is immediately apparent from Map 5 that the flood risk areas defined by the Environment Agency and those inferred in this report differ. Though the areas designated by the Environment Agency are generally included within the alluvial tracts identified by the BGS, the latter is generally of wider extent and locally, as to the south-west of Lampeter, significantly so. Some of these differences may reflect variations in remit. Other differences may reflect differing methods of data collection and map production. The Environment Agency maps are based principally on observations of actual flood levels, historical data from newspapers and anecdotal evidence from landowners, together with some topographical extrapolation. The BGS maps are based almost exclusively on geological and geomorphological features mapped in the field, though with regard to information from by landowners. The Environment Agency maps therefore show limits of areas

Plate 19 Afon Teifi in flood below Cenarth Bridge [2687 4154].

known to flood because it has been witnessed it, or in some instances modelled; the BGS data shows areas known to flood because river flood deposits and their landforms are preserved. Though both concepts are equally valid, the detailed ground surveying undertaken as part of this project suggests that some of the Environment Agency linework may be in need of emendation.

7.9.6 Flood return limits

The Institute of Hydrology (NERC) has recently developed and published computer-based flood risk mapping on national scale (Morris and Flavin, 1996). The maps, at the scale of 1:625 000, show an estimate of the area that would be inundated by the 100-year flood (the flood which has a 1:100 chance of occurring in a given year) from non-tidal rivers in the absence of flood defences. The extent of the '100-year flood' in the Teifi valley approximates much closer to the present day flood plain and first terrace of the main river than the Environment Agency Flood Risk Area.

It is possible therefore to speculate on how the Environment Agency and BGS data sets for the Afon Teifi catchment can be interpreted in terms of flood return limits. The flood risk areas outlined by the Environment Agency may principally enclose those parts of the active flood plain prone to flood most frequently; areas which flood annually or certainly once a decade, broadly defining a 1–10 year flood return limit. The generally wider belts of alluvium surveyed by the BGS, though they delineate the active floodplains of the Teifi and its tributaries as defined using geological and geomorphological criteria, may be completely flooded rather less frequently. Together with the first terrace, their outer limits perhaps approximate to the 100-year year flood return limit. Though many of the first terraces of the catchment were flooded during the 1987 event, the presence of dwellings on these surfaces suggests that they mostly lie outside the limit of regular decadal flooding. The second terraces will be flooded still less frequently. The highest terrace surfaces lie within the return limits of rare, monumental floods which occur probably thousands of years apart.

8 Landslips and slope steepness — Thematic Map 6

Evidence of slope instability due to landslip is found throughout the catchment, with some 385 individual sites being recorded during the survey. If development pressures, particularly for housing and improved infrastructure, lead to building on unstable or potentially unstable ground, there is an increased possibility of encountering slope instability associated with existing landslips, or of creating the conditions whereby land may become unstable. **However, if proper site investigations are undertaken on unstable or potentially unstable ground, and suitable preventative or remedial measures are employed, the majority of problems may be overcome.**

The distribution of existing landslips is a major pointer to where future slope movements may occur. Existing landslips, identified during the survey, are shown on Thematic Map 6, with the location approximating to the mid-point of each slip. The larger areas of landslip on the map generally consist of a series of individual adjacent slips, commonly found along the valley sides of tributaries of the Afon Teifi; however, they also include the large, complex landslips of St Dogmaels (Plate 20) and Newcastle Emlyn. The distribution of landslips is presented on a slope map, derived from Ordnance Survey Digital Terrain Modelling (DTM) data.

8.1 LANDSLIP TYPES

Landslips are the downslope mass movement of soil and/or rock under the influence of gravity. Movement may be slow to very rapid, and either continuous or subject to intermittent surges. The scale of such movements varies, and landslips within the catchment range from a few square metres to large failures involving tens of hectares. A landslip occurs, when, either the strength of the material (soil, rock) is exceeded by the loading forces (self weight, augmented by building, tipping etc.) acting upon it, or there is a corresponding reduction in the resisting forces by erosion or excavation. Once movement has occurred, the resisting strength of the landslipped material is reduced close to residual values, and further movement becomes more likely if there is any change in the conditions at the site. These changes can be brought about by natural processes such as river erosion removing support at the toe of the slip, or heavy rainfall, which can saturate the landslip, adding weight and increasing pore pressures, thereby further reducing the strength of the slip material. Adverse changes due to human influences are numerous, but include top-loading of the slip by construction and the placing of fills, removal of support by excavation, and the introduction of increased water volumes by drainage diversion, pipeline leakage or soakaways.

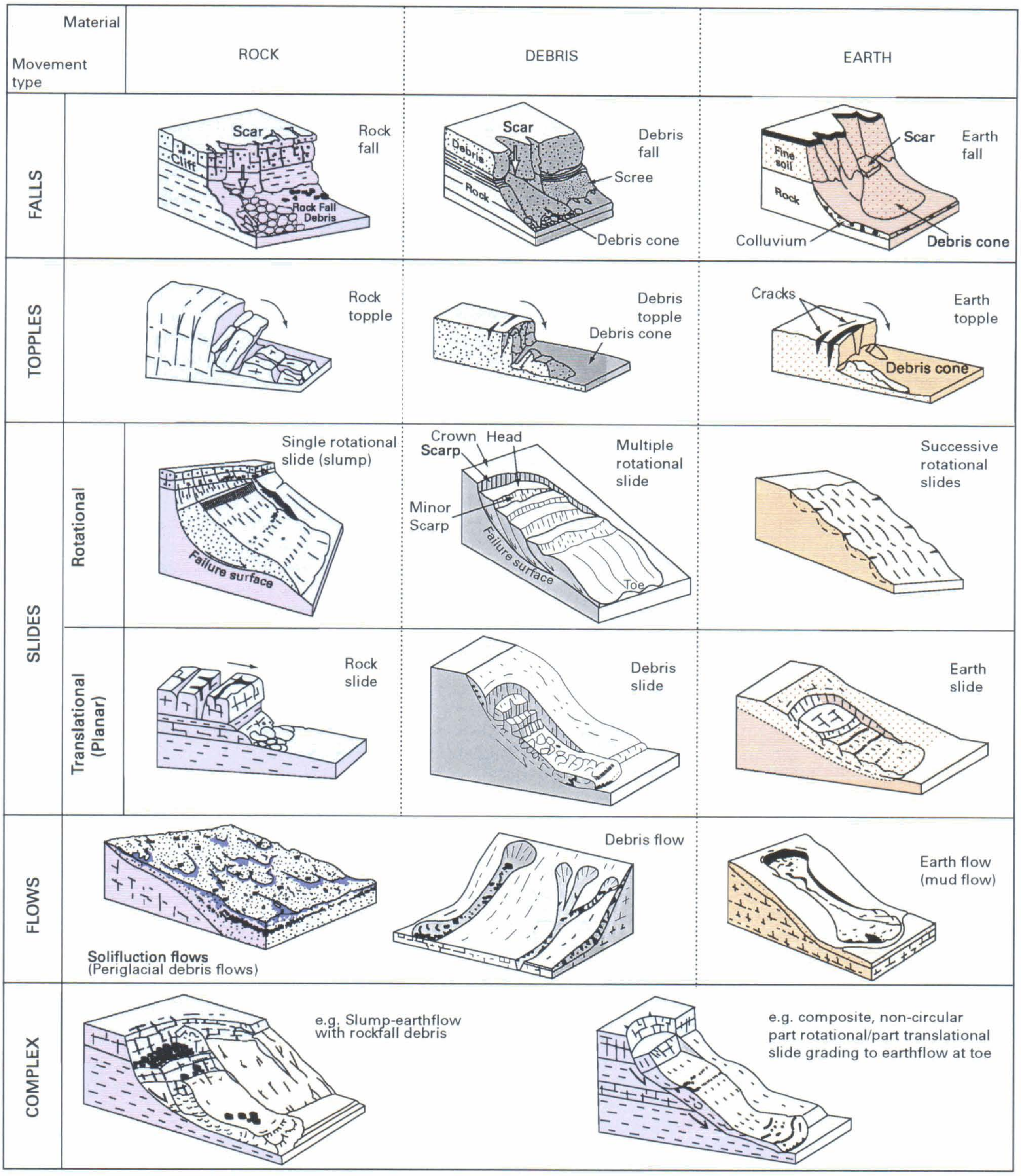
The most commonly used classification scheme to describe the various types of landslip is that of Varnes (1978), which is reproduced with minor modification in Figure 9. It is essentially based on the type of movement (i.e. mode of failure), and involves consideration of the initial rupture surface, the dominant form of displacement, the type of displaced material and its behaviour as it undergoes displacement. The main forms of displacement according to this classification are:

Falls, where material detaches from a steep slope or cliff.

Slides, where material moves along a recognisable shear surface (or surfaces), either planar (*translational slides*) or curved (*rotational slides*).

Flows of saturated, viscous materials, which may move at various rates downslope.
Complex landslips combining two or more of these movement types.

Plate 20 Upper section of the St Dogmaels Landslip in February 1994; note fresh landslip scars and fissures in green fields (upper centre) and waste tip (centre right) [1578 4543].



Falls mass detached from steep slope/cliff along surface with little or no shear displacement, descends mostly through the air by free fall, bouncing or rolling.
Topples forward rotation about a pivot point.
Rotational slides sliding outwards and downwards on one or more concave-upward failure surfaces.
Translational (planar) slides sliding on a planar failure surface running more-or less parallel to the slope.

Flows slow to rapid mass movements in saturated materials which advance by viscous flow, usually following initial sliding movement. Some flows may be bounded by basal and marginal shear surfaces but the dominan movement of the displaced mass is by flowage.
Complex slides slides involving two or more of the main movement types in combination.

Figure 9 Classification of type of landslip (modified after Varnes, 1978 and DoE, 1990).

The importance of the material involved in the slip is recognised in the classification by further subdivision based on:

Rock (i.e bedrock).

Debris, consisting of coarse-grained engineering soils (gravel-size fractions and above).

Earth, comprising fine-grained engineering soils (dominated by clay- to sand-sized fractions).

The majority of landslips in the catchment are relatively shallow, earth and debris slides, involving a range of complex movements including components of translation, rotation and flow. Flows rarely occur as individual features, but are commonly developed in the lower parts of slips as earth or debris flow aprons. Many slides show more than one phase of movement, and in certain large landslips such as St Dogmaels and Newcastle Emlyn, there may be both active and passive slip elements. These types of composite slip are often characterised by an irregular topography which commonly promotes ponding of water from springs, seeps and surface runoff, thereby maintaining such landslips in a state of marginal stability. In some areas within the catchment, old, degraded and vegetated landslip features are present, and locally landslips may have been obscured by dense woodland, agriculture and building development. **For these reasons it should not be assumed that all landslips have been identified during the present geological survey.**

8.2 HISTORY OF LANDSLIP IN THE CATCHMENT

The present geological survey has shown that there has been a long history of landslip within the catchment, dating back to the later stages of the Devensian glaciation around 10 000 years ago (Figure 3). A number of landslips, particularly the larger and complex types, probably developed initially in response to conditions very different to those of today. At the end of the last glaciation, there was local downslope movement of saturated, deeply weathered and partially frozen material, on the glacially oversteepened slopes. As the climate ameliorated, these landslips became progressively dormant, degraded and vegetated, and now have very subdued surface expressions. Under present conditions such areas may remain dormant, unless the factors controlling stability are disturbed by natural processes or human interference.

Landslips continue to be active within the Afon Teifi catchment, and the present survey has identified up to 141 sites (37%) where movement is currently taking place, or has done so in recent years (Figure 10). Active landslips have been identified by visual inspection, and are characterised by the freshness of their landforms, the lack of vegetation on slip scars, and recent damage to buildings and services. In a number of cases, remedial measures to stabilise these landslips have been completed, as in the road schemes at Troedyrhiw, Alltybwla, Plasgeler and Alltyblacca, listed in the database of geotechnical reports (Appendix 1). The large landslip of St Dogmaels, which became noticeably active in January to February 1994, is likely to be stabilised by engineering works in the near future; it appears to be a reactivation of a much earlier slip in glaciolacustrine clays, and probably has a long history of movement dating from late-glacial times (Hobbs et al., 1994; Maddison et al., 1997) (Plates 20, 21 and 22). Newcastle Emlyn, which has a legacy of landslip problems along the bank of the Afon Teifi, is currently being assessed.

It should be stressed that the occurrence of landslips within the Afon Teifi catchment, other than the examples quoted above, does not present as great problem to development as might at first appear. The majority of the 385 landslips identified, occur on agricultural land, remote from potential development sites. In terms of the area surveyed, landslip frequency only amounts to 1 per sq km and, away from complex drift sequences of the catchment, this proportion is anticipated to be considerably less. Apart from the sites at St Dogmaels and Newcastle Emlyn, which affect a considerable number of properties, there are only 30 to 40 additional dwellings and businesses situated on landslips, of which only about ten percent show any obvious signs of damage.

8.3 PRINCIPAL CAUSES OF LANDSLIP

The susceptibility of ground to landslip is governed by the predisposition factors that make it marginally stable and triggering factors that eventually cause it to become actively unstable. Predisposition factors are dominated by slope angle and geology (lithology and structure), but include local drainage and groundwater conditions, and weathering. Triggering factors include changes to the local drainage or groundwater conditions, commonly caused by increased rainfall, loading, erosion of the toe of a slope or existing landslip, and human interference.

Although landslips are present in most areas of the Afon Teifi catchment, the current geological survey has identified a number of situations in which they recur. Generation of a landslip requires the presence of an initial slope, and slips within the catchment are invariably found on valley sides. The interfluves and flat upland areas are largely devoid of landslips, as are the steepest slopes, where solid rock outcrops under a thin veneer of regolith.

The overwhelming majority of landslips (99%) are found in drift deposits (Figure 11) on the lower slopes of valleys (Figure 12). The bulk of these (74%) fall almost equally into three groups of glacial drift, namely till, glaciolacustrine deposits and glaciofluvial deposits (Plate 23); the remainder are made up of undifferentiated glacial deposits (10%) and periglacial head deposits (mainly head gravels; 13%) (Figures 13 and 14). Later post-glacial alluvial sediments, which floor all the major valleys, and generally have no slope component, contain few landslips; only four have been recorded in river terrace deposits, where active river undercutting has destabilised the bank. Landslips in rock are very uncommon, and usually occur in the weathered bedrock/regolith profile, or are due to particular geological circumstances such as alignment of bedding and/or cleavage or joints with slope (Plate 24).

In general, it is not possible to highlight any single type of drift deposit as being more or less prone to slip. However, geological investigations associated with the St Dogmaels landslip indicated that glaciolacustrine deposits, especially clays, underlay much of the landslipped area at depth (Fletcher, 1996). Therefore, during the present survey, particular attention was paid to the distribution of these deposits, either at surface, or where they were known or suspected to be present at shallow depth beneath other landslipped materials. Although the glaciolacustrine clays form only 24% of landslips at surface, mapping suggests that

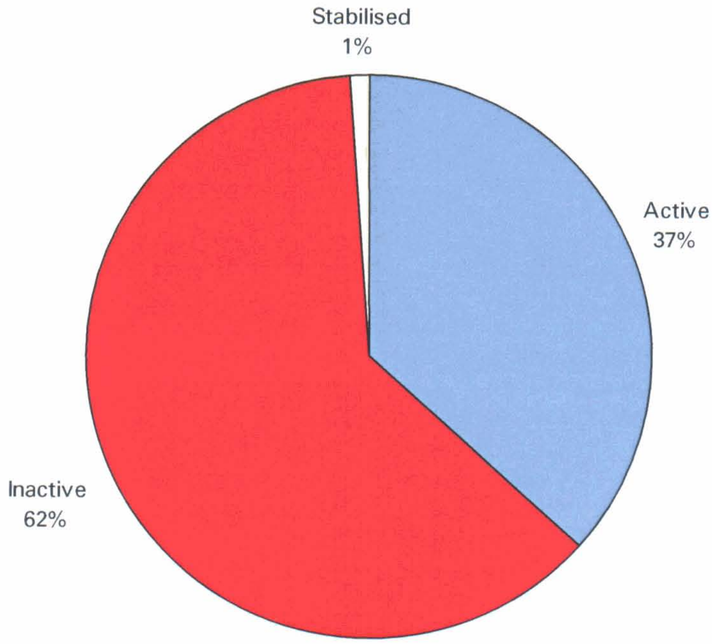


Figure 10 State of activity of landslips.

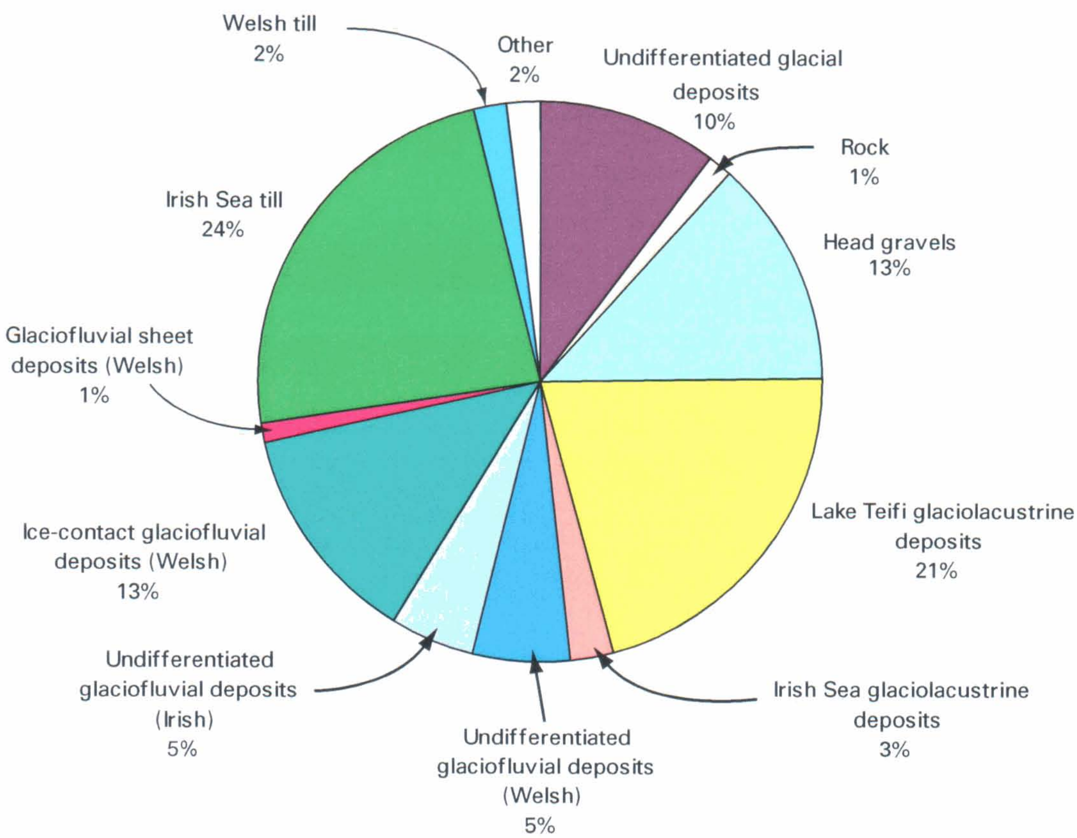


Figure 11 Lithological categories of landslips.

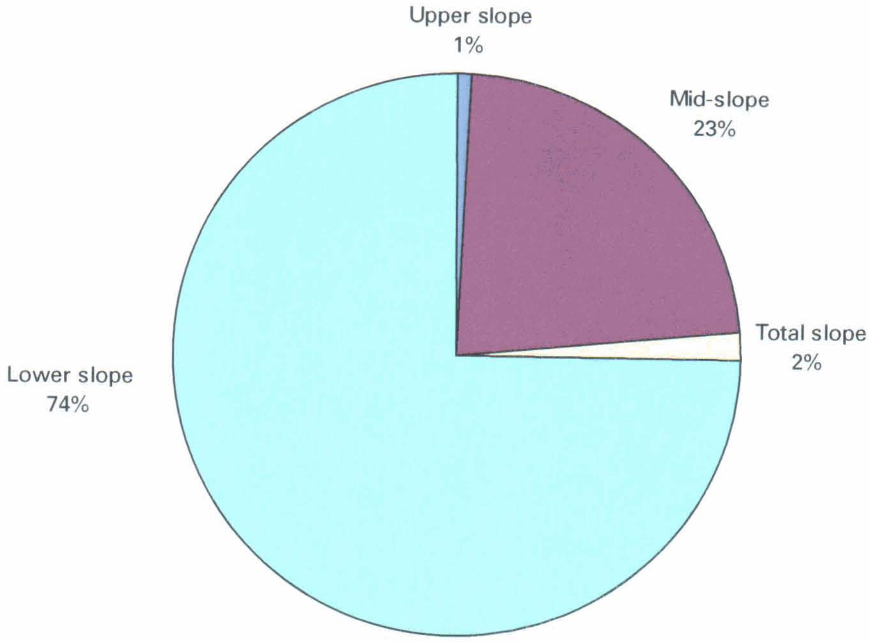


Figure 12 Position of landslips on valley-side slopes.

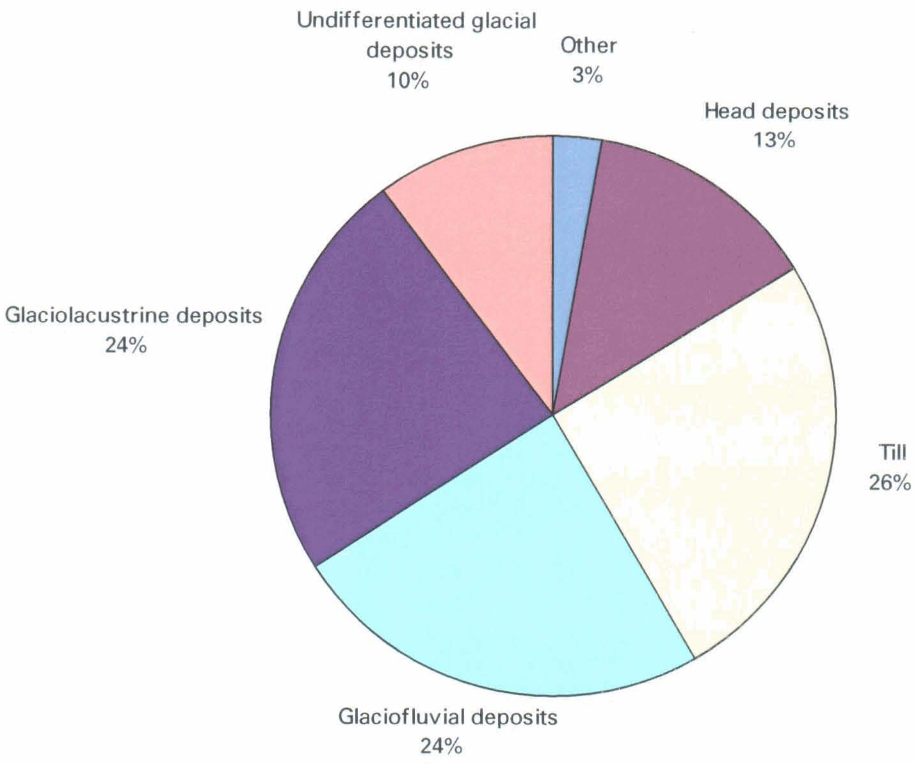


Figure 13 Lithological groupings of landslips.

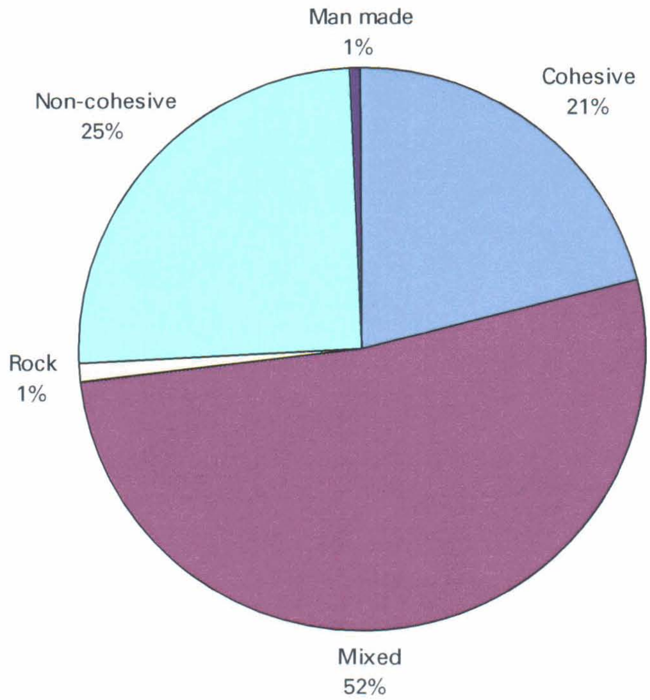


Figure 14 Engineering classification of landslip geology.

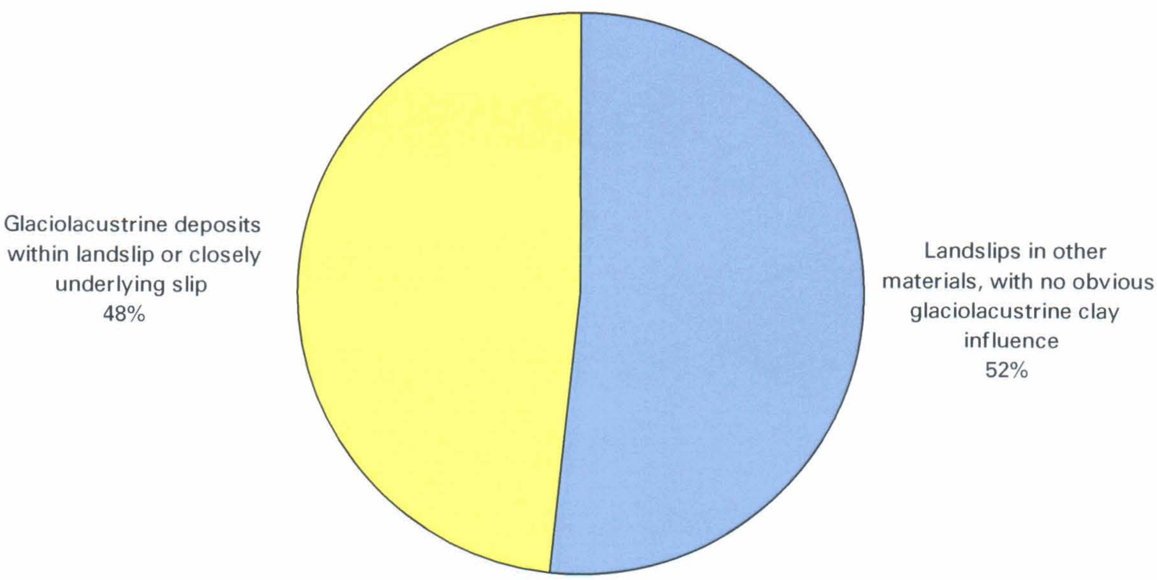


Figure 15 Glaciolacustrine deposits involved in landslips.

Plate 21 Cracking in walls of Bryncws Cottage [1600 4575], north-western side of St Dogmaels Landslide.

Other common landslip triggers include impeded drainage, where the strength of the slip material has been significantly reduced by water. Landslips of this type are commonly associated with springlines, usually above an impermeable substrate, and account for 11% of cases. Landslip triggered by human activity only account for a few cases. In most instances these slips are due to excavations, which have either created unstable slopes or removed support from the toes of existing slips.

It should be emphasised that the factors discussed above are the principal causes of slope failure within the Afon Teifi catchment. The reasons for movement within an individual landslip are a combination of predisposition and triggering factors, the relative importance of which may increase or decrease with time.

8.4 RECOMMENDATIONS FOR PLANNING AND DEVELOPMENT

The present survey indicates that glaciolacustrine deposits are involved in a significant number of landslips, either as the principal lithology within the slip, or as the deposit closely underlying the slipped material. It is therefore recommended that, in terms of development, special attention should be given to situations where these clays are present at surface or are believed to occur at shallow depth beneath other deposits.

Other instances in which landslips occur, generally depend on a combination of predisposition and triggering factors, the most common of which is the association of

they closely underlie at least a further 24% of others (Figures 11 and 15). They are, therefore, an important factor in considering the stability of overlying deposits, in situations where landslips are likely to occur. An assessment of the way in which these clays have contributed to instability within individual landslips is beyond the scope of this report, but the general means by which the clays may promote failure of the overlying materials is considered to be by:

- *impounding water in the overlying and/or underlying materials* (because of the clays, highly impermeable nature), thereby reducing their strength
- *valleyward creep and flow* (due to the low residual strength of the highly plastic, soft, weathered clays), which may cause rupture in the overlying materials

The dominant trigger for landslips in drift in the Afon Teifi catchment is related to river erosion resulting in the removal of material from the base of a slope or the toe of an existing slip. There are two common scenarios where this is apparent. The first occurs along the sides of tributary valleys to the Afon Teifi, where clayey lithologies (tills, glaciolacustrine clays, etc.) have undergone rapid downcutting by the river since the end of the last glaciation; this process continues to the present day, and has resulted in a series of elongate slips along the valley sides. The second situation is found in the main Teifi valley, where the meandering river has impinged on poorly cohesive glaciofluvial gravels, river terrace and head gravels, at intervals along its length; this has led to a number of isolated slips on the outer part of meanders (Plate 23).

Plate 22 Cracking in walls and driveway, Fford y Cwm [1630 4575], central part of St Dogmaels Landslide.

Plate 23 Rotational landslip in glaciofluvial sheet deposits, south bank of Afon Teifi [5682 4665], 300 m north of Felinfach

glacial deposits in a state of marginal stability along the flanks of valleys, where there is active river erosion; development in these situations may trigger instability, and attention should be given to each site on an individual basis.

The most effective strategy for dealing with unstable, or potentially unstable ground hinges on recognition of problem areas in advance of development. Avoidance of these areas, or pre-emptive work will usually be less traumatic and costly than remedial work after movement has occurred. Preliminary assessment of slope instability at proposed development sites, involving desk study of available information and walkover inspections, should be carried out at the earliest possible stage, and prior to planning site investigations. Engineering geomorphological mapping of the site and its environs is advisable, at scales appropriate to the development and to the potential problem, and should be standard practice at the feasibility stage of construction projects in areas of existing or potential landslip. These preliminary inspections serve to assess areas surrounding proposed development sites as to the presence and likely influences of landslips on adjacent slopes, or the potential threat to neighbouring land should a landslip be triggered by construction. Preliminary inspections and mapping also enable greater precision, and hence cost effectiveness, in the design of the site investigation programme. Planning Policy Guidance Note 14 (Department of the Environment, 1990) recommends the BGS as a prime source of data relating to ground instability; BGS also has the necessary expertise to undertake preliminary surveys (including geomorphological and geotechnical surveys) of land suspected to be unstable. Site investigations should be designed to establish the factors controlling stability (or instability) and, where present, the dimensions of existing landslips. Investigation should not be restricted to the development site, but should include surrounding areas where stability problems may also occur. It is essential that investigations obtain sufficient data to perform valid stability analyses, including surveyed slope angles, type and depth of movement, position of basal and intra-slip shear surfaces or zones, the strength of the slope materials and the maximum water table or pore water pressure within the slope (monitored over a suitable period). Material strengths should be tested on high-quality, undisturbed samples, which, for shallow depths, are most easily recovered from trial pits; deeper samples will require borehole recovery. The extensive use of trial pits is strongly recommended for landslip investigations as a relatively cheap and effective way of examining large sections of slope materials. **However, it is emphasised that trial pitting in landslipped ground is hazardous, and should only be undertaken by competent geotechnical contractors with previous experience of excavating in similar conditions.**

Past experience reveals that ground and groundwater conditions may vary unpredictably over relatively short

Plate 24 Rockfall, south side of A484 [5257 4091], near Newcastle Emlyn.

distances. Consequently, conditions pertaining at one locality can not be extrapolated to apparently similar sites nearby. Accurate assessment of stability may only be determined reliably from data obtained at individual sites. In some cases where existing development is on, or threatened by landslip, long-term slope monitoring may be required to ascertain the activity of the slope.

The cost of comprehensive site investigation to establish stability parameters may be significant, even for a relatively small landslip; site investigations of small slips associated with on-going river bank erosion are probably not cost-effective. On large schemes expenditure may escalate unless the objectives of the work are closely defined. For minor constructions (e.g. garages or small extensions) a full-scale investigation may not be practical. Planning Policy Guidance 14, Annex 1 (Department of the Environment, 1996) suggests that construction of such lightweight structures, without site investigation, may be acceptable, providing the site is not significantly disturbed. However, such provisos should be confirmed only after inspection from a competent professional.

For planning purposes, landslip sites and areas which may be susceptible to ground movement should be avoided if at all possible. However, if development on ground proved to be unstable by site investigation cannot be avoided, it must be made stable by appropriate engineered remedial works prior to development. Such work is a specialist task that should only be carried out under the supervision of a competent engineer. It may involve a number of remedial measures, including one or more of the following:

- *Increasing soil strength* by total or partial excavation of landslip material and replacement with stronger material. This is most applicable to small slips, particularly where the existing slope geometry must be maintained and replacement with free-draining granular material is economical.
- *Modifying the mass distribution* by adding weight to the toe, removing material from the crest, reducing overall height, flattening the slope or a combination of these.
- *Reduction of pore pressures* in the slope by drainage; this may include a number of surface and/or subsurface drainage techniques, used either singly or in combination.
- *External restraints* such as ground anchors, piles, counterforts or deep retaining walls keyed into undisturbed deposits.

The selection of appropriate remedial works may depend not only on geotechnical considerations, but also on constraints placed on sites by environmental factors, accessibility and existing development. However, of the remedial options available, that of drainage is particularly important.

Water is always a contributing factor in the failure of both natural and man-made slopes. Consequently, whatever the main remedial action may be, attention to drainage is vital if only to ensure that existing drainage is not impeded by the remedial works. For large landslips, drainage improvements may be the only option, and in minor cases drainage measures may be effective in themselves. Correct and careful drainage installation is vital to performance, as is maintenance of the installation to prevent deterioration. Attention to surface and subsurface drainage from existing dwellings is of particular importance for those on or near areas with known or potential stability problems. Adherence to simple measures outlined in Policy Planning Guidance 14, Annex 1 (Department of the Environment, 1996) may guard against potentially damaging movements and prevent the need for costly remedial works once instability has been initiated.

The presence of landslip does not preclude development, provided the problem is recognised, properly evaluated and effectively remedied and maintained.

GEOTECHNICAL REPORTS AND BOREHOLE DATA SOURCES

1:10k Sheet No	S.I. Reports	BGS S.I. Reference No.	Confidentiality	Date	Brief Title	Company Reference No.	Contractor	Consultant	Geotech. data	Boreholes	Trial Pits	Borehole/ Trial Pit Reference Nos (BGS)	New Data
SN13NW	Y	10391	N	May-91	Eglwyswrw S.T.W.	7414/1417	Thyssen Construction Services Ltd	Wallace Evans & Partners	Y		5	1-5	Y
SN14NE	Y	10353	Y	Oct-94	Afon Mwldan Flood Alleviation Scheme (1	154092	Exploration Associates Ltd	WS Atkins (Wales) Ltd	Y	11		54-64	Y
SN14NE	Y	10432	Y	Dec-94	St Dogmaels Landslide (4 vols) (1)	KC/SDL/R2	Exploration Associates Ltd	Sir Wm Halcrow & Partners	Y	26	20	97-142	Y
SN14NE	Y	10387	N	Feb-88	Culvert at Bath House, Cardigan	7414/893	Thyssen (Great Britain) Ltd		N	1		65	Y
SN14NE	Y	10384	N	Aug-94	Cardigan Bridge: Phase Two	7640/109	Thyssen Geotechnical	Veryards Ltd	Y	3		153-155	Y
SN14NE	Y	10381	N	May-95	Dolwerdd Playing Fields, Cardigan	A50200	Thyssen Geotechnical	Richard Broun Associates	Y	5	6	37-47	Y
SN14NE	Y	10373	N	Apr-91	Cardigan Library	7414/1419	Thyssen Construction Services Ltd		Y		6	48-53	Y
SN14NE	Y	3408	N	May-68	Footbridge at Cardigan Bridge (1)	FC/154	Pre-Piling Surveys Ltd		N	2		2-3	N
SN14NE	Y	3407	N	Nov-69	Footbridge at Cardigan Bridge (2)	363	Robertson Research Co. Ltd		N	2		1-1a	N
SN14NE	Y	3409	N	Sep-72	Cardigan By-pass (2 Vols) (1)	CF669/910	Foundation Engineering Ltd	G Maunsell & Partners	Y	20	5	4-28	N
SN14NE	Y	10423	Y	Jan-89	Prince Charles Quay, Cardigan (1)	3372	Norwest Holst Soil Eng Ltd	Gifford and Partners	N	3		91-93	Y
SN14NE	Y	10383	N	Nov-93	Prince Charles Quay, Cardigan (2)	7640/43	Thyssen Geotechnical	Howard Humphreys & Partr	Y	3		94-96	Y
SN14NE	Y	10392	N	Jul-78	Shire Hall, Cardigan	2.156.0	Thyssen (Great Britain) Ltd	Howard Humphreys & Partr	N	2		83-84	Y
SN14NE	Y	10429	N	Sep-89	Cardigan Secondary School	TCES/89/235	T.C. Engineering Services		N		6	85-90	Y
SN14NE	Y	10422	N	Dec-91	South Wales Sand & Gravel Resources	PECD 7/1/382	University of Liverpool		Y			1*, 2-3 ‡ 151-2 †	Y
SN14NE	N		Y	Mar-95	Afon Mwldan Flood Alleviation Scheme (2	A50190	Thyssen Geotechnical	WS Atkins (Wales) Ltd	N	2		70-71	Y
SN14NE	N		Y	May-96	Afon Mwldan Flood Alleviation Scheme (3	A50190	Thyssen Geotechnical	WS Atkins (Wales) Ltd	N	7	10	157-173	Y
SN14NE	N		Y	May-96	Afon Mwldan Flood Alleviation Scheme (4	A60321	Thyssen Geotechnical	WS Atkins (Wales) Ltd	N	13	10	174-195	Y
SN14NE	N		Y	Dec-96	Cardigan W.W.T.W.	A60459	Thyssen Geotechnical	Hyder Consulting Ltd	N	3	4	76-82	Y
SN14NE	N		N	Mar-97	BGS Cardigan No 1 (Llwynpiod) Borehole		Exploration Associates Ltd		N	1		156	Y
SN14NE	N		Y		St Dogmaels Landslide (2)	154053	Exploration Associates Ltd	Ove Arup	N	3	5	143-150	Y
SN14NE	N		N	Feb-79	Cardigan By-pass (2)	74014/211	Thyssen (Great Britain) Ltd		N		7	30-36	N
SN14SE	Y	5749	Y	Dec-89	Cardigan Radio Station	SM761	CEGB Engineering Dept.		N		1	1	N
SN14SE	Y	6162	N	Apr-80	Troedyrhiw Landslip (1)	S2525	Exploration Associates Ltd		Y	5		7-11	N
SN14SE	Y	6162	N	Jan-82	Troedyrhiw Landslip (2)	F4955B	Norwest Holst Soil Eng. Ltd		Y	6		2-6, 29 †	N
SN14SE	N		N	Mar-97	BGS Cardigan No 2 (Penbryn) Borehole		Exploration Associates Ltd		N	1		12	Y
SN14SW	Y	10393	Y	Jul-96	Pantgwyn Quarry, Cardigan	A60366A	Thyssen Geotechnical	Wyn Thomas PLC	Y	3	9	40-51	Y
SN24NW	Y	10375	Y	Dec-89	Cilbronnau Farm, Llangoedmor	7414/1217	Thyssen (Great Britain) Ltd	T Hopkins (Architect)	Y	1		1	Y
SN24SE	Y	10396	N	Dec-69	Ceri Bridge, Cwmcou		Geo-research Ltd	Wallace Evans & Partners	Y	2		4-5	Y
SN24SE	N		N	Jun-78	Pont Ystrad, Cenarth		Geo-research Ltd		N	3		1-3	N
SN24SE	N		N	May-88	Alltybwla Landslip	7414/961	Thyssen Geotechnical		N	3		6-8	Y
SN24SW	Y	10379	Y	Nov-96	St Tygwydd Church, Llandygwydd	A60407	Thyssen Geotechnical	Preece Thomas Partnership	Y	2	1	6-8	Y
SN24SW	Y	10371	Y	Jul-90	Llechryd S.T.W.	7414/1229	Thyssen Construction Services Ltd	Wallace Evans Ltd	Y	4		2-5	Y
SN24SW	Y	10433	N	Mar-79	Llechryd W.T.W. (1)	74014/209	Thyssen (Great Britain) Ltd		Y	7	1	9-16	Y

GEOTECHNICAL REPORTS AND BOREHOLE DATA SOURCES

1:10k Sheet No	S.I. Reports	BGS S.I. Reference No.	Confidentiality	Date	Brief Title	Company Reference No.	Contractor	Consultant	Geotech. data	Boreholes	Trial Pits	Borehole/ Trial Pit Reference Nos (BGS)	New Data
SN24SW	N		N	Sep-96	Llechryd W.T.W. (2)				N		4	17-20	Y
SN33NE	Y	10374	N	May-91	Parc Puw, Drefach - Felindre	7414/1427	Thyssen Construction Services Ltd		Y		6	14-19	Y
SN33NE	Y	6200	N	Dec-74	A484: Llangeler Diversion	SI.1940/F.2892	Norwest Holst Soil Eng Ltd	Wallace Evans & Partners	Y	13	11	1-24	Y
SN33NE	Y	10386	N	Nov-89	Plasgeler Landslip (2)	7605/4	Thyssen Geotechnical		Y	3		22-24	Y
SN33NE	N		N	May-88	Plasgeler Landslip (1)	7414/964	Thyssen Geotechnical	M.R.M. Partnership	Y	2		20-21	Y
SN34SE	N		N	Jan-71	Pontbargoed Bridge	8358/GPG	Cementation Ground Engineering		N	2		1-2	N
SN34SW	Y	10409	Y	Oct-92	Sycamore St. Newcastle Emlyn (1)	2745/DMB		D M Bodycombe	N				Y
SN34SW	Y	10389	Y	Nov-92	Sycamore St. Newcastle Emlyn (2)	7414/8077	Thyssen Geotechnical	Mel Williams Partnership	N				Y
SN34SW	Y	10372	N	Dec-91	Ebenezer Chapel, Newcastle Emlyn (1)	7414/1486	Thyssen Construction Services Ltd		Y	4	7	6-16	Y
SN34SW	Y	10380	N	Mar-93	Ebenezer Chapel, Newcastle Emlyn (2)	7640/06	Thyssen Geotechnical		N	2		4-5	Y
SN34SW	Y	10388	N	Jan-93	Newcastle Emlyn Secondary School	74014/433	Thyssen (Great Britain) Ltd		N		3	23-25	Y
SN34SW	Y	10390	N	Nov-89	Castle Street Car Park, Newcastle Emlyn	7414/1195	Thyssen Geotechnical		N	3	1	19-22	Y
SN34SW	Y	10395	Y	Feb-92	Teifi Sawmills, Newcastle Emlyn	9153045	Exploration Associates Ltd	Golder Associates (UK) Ltd	Y	2		17-18	Y
SN34SW	N		N		A484: Aberarad Landslip	830872	Ground Engineering Ltd		N	3		1-3	N
SN43NW	Y	10376	N	Jan-88	Pencader County Primary School	7414/859	Thyssen (Great Britain) Ltd		Y		6	1-6	Y
SN43NW	N		N	Mar-85	Gwenfaes, Pencader	74014/	Thyssen (Great Britain) Ltd	Mel Williams Partnership	N	2	5	7-13	N
SN54NE	Y	10382	Y	Jan-85	Students Union Building, Lampeter	74014/554	Thyssen (Great Britain) Ltd	Clarke, Nichols & Marcel	Y	1		8	Y
SN54NE	Y	10377	Y	Sep-87	Lampeter S.T.W.	7414/858	Thyssen (Great Britain) Ltd		Y	4		9-12	Y
SN54NE	N		N	Sep-92	Lampeter University Teaching Block	30371/SR390	Applied Geology	Wyatt and Watts	N	3		5-7	N
SN54NW	Y	6162	N	Oct-81	Alltyblacca	F4955B	Norwest Holst Soil Eng. Ltd		Y	3		2-4	N
SN54SW	Y	10378	N	Jul-95	A485: Henfaes Bridge	A50159/4	Thyssen Geotechnical		Y	5		3-7	Y
SN54SW	N		N	Jan-79	Rhydbont, Llanybyther	2336/E	Geo-research Ltd		N	2		1-2	N
SN64NW	Y	10385	Y	Sep-96	Cellan S.T.W.	A60396	Thyssen Geotechnical	Hyder Consulting Ltd	Y	4	8	1-12	Y

Borehole data also on SN14NW *

Borehole data also on SN14NE †

Borehole data also on SN24NW ‡

Appendix 2 — Geophysical investigations

INTRODUCTION

Background

The aim of this geophysical survey was to provide information on the nature and thickness of superficial deposits lying in buried valleys that form the abandoned sections of the Afon Teifi drainage system. The study area extended for about 35 km inland from the coast at Cardigan (Figure 16). In particular, there was a requirement to define depths to bedrock so that boreholes could be sited in the deepest parts of the buried valleys, thus allowing the maximum thickness of fill to be sampled.

With the limited resources available for the survey, an approach combining gravity and resistivity techniques was adopted in order to maximise the number of sites that could be included. Previous geophysical studies in this area, using seismic refraction (Allen, 1960; Francis, 1964) and reflection (Nunn and Boztas, 1976) techniques had indicated maximim depths to bedrock of 50 to 70 m beneath the valley floor. Such results are generally better constrained than gravity or resistivity interpretations but are slower and more expensive to acquire.

Regional gravity data for the district provided evidence that the gravity method should be effective. Although the station coverage is only about 1 station per 1 to 1.5 km^2, the few stations located within the Teifi valley generally show anomalously low values. The gravity map (Figure 17) is dominated by the regional increase in values towards the Irish Sea. However, a residual anomaly map (Figure 18) highlights the local features, which comprise a series of lows, manifested as isolated 'bullseyes'. This is due to the station spacing being large compared to the wavelength of the anomalies in question. A more detailed survey however, would almost certainly establish the continuity of residual anomaly values associated with the buried valleys along the Teifi valley.

Gravity anomalies of about 1 mGal were predicted on the basis of the large density contrast between slate grade Ordovician bedrock and the unconsolidated superficial deposits (till, clays, sands and gravels) comprising the valley fill. These would be easily resolved given a typical measurement accuracy of <0.05 mGal. Resistivity values, which depend mainly on clay content and effective porosity, provide an independent guide to changes in lithology and formation thickness. Thus, joint interpretation of the two data sets helps in constraining the final models, reducing the ambiguities inherent to each technique when used independently.

Traverses were sited to cross abandoned courses of the Afon Teifi, either as identified or inferred by the mapping geologists. One of the traverses (GT3) was located close to the seismic refraction line near Cenarth (Francis, 1964), where a maximum depth to bedrock of 70 m had been interpreted, as an aid to calibrating density and resistivity values. Traverses GT1 and GT4a ran through the town centres of Cardigan and Newcastle Emlyn respectively but the others went across country, taking in roads and farm tracks where practical. The relief was relatively subdued across the valley floor, although there was a marked increase in slope at the margins. Some difficulty was found in siting the resistivity soundings due to undulating terrain, the limitations of field boundaries and the presence of roads. The fieldwork was conducted in mainly dry weather between 29th September and 12th October 1996, when access to the low-lying cattle pasture presented no difficulty.

Geological Setting

Over most of the western part of the area, bedrock is formed by mudstones of the Nantmel Mudstones Formation, but interbedded sandstones and mudstones of the underlying Moylgrove Group are present near the coast in a fault slice between traverses GT1a and GT1. In the eastern part of the area, bedrock comprises mudstones with scattered units of thick sandstones of the Yr Allt Formation beneath the line GT5, and interbedded mudstones and sandstones of the succeeding Cwmere Formation beneath line GT6.

In pre-glacial times the Afon Teifi deposited sands and gravels in a deeply-incised, wide, meandering valley. With the onset of the late Pleistocene glaciation, glaciolacustrine clays were laid down in a proglacial lake formed between an Irish Sea ice sheet just offshore of the present estuary, and Welsh ice advancing into the upper reaches of the catchment from the Cambrian Mountains. The subsequent advance and eventual retreat of both ice sheets saw the deposition of a wide variety of tills and glacial sands and gravels along the Teifi valley, its tributaries and, locally, on the interfluves. Following the retreat of the ice, the Afon Teifi cut down through the glacial deposits filling the valley to give a pattern of superimposed drainage. This comprises wide alluvial tracts, alternating with narrow rock gorges which bypass abandoned meander loops.

The initial model for the fill of the buried valleys assumed that river gravels and sand beds would overlie the Lower Palaeozoic bedrock; these would be succeeded by glaciolacustrine deposits and, locally, by a later cover of till or glacial gravels, with head, comprising mudstone fragments in a silty matrix, on the valley sides.

GEOPHYSICAL METHODS

Gravity

Differences in rock density produce small changes in the Earth's gravity field that can be measured using sensitive gravity meters. However, other factors, such as the shape of the Earth and ground elevation, tend to mask these variations and so the observed field data are usually converted into Bouguer anomaly values, which take into account the effects of instrumental drift and differences in Earth tides, latitude, height above sea level, thickness of rock between the station and sea level, and ground relief at each station.

Variations in normal gravity relating to the non-spherical shape of the Earth can be calculated from standard formulae (GRF67 was used here) and are such that latitude must be known to within 10 m, to achieve an accuracy in the Bouguer gravity anomaly of 0.01 mGal; similarly, station elevations are required to 0.05 m to correct for the reduction in the Earth's gravity field with increasing height. The average density of the rocks down to sea level used in the Bouguer correction is generally assumed on the basis of the expected geology and values derived from laboratory measurements on related rock types.

Gravity data were collected using a Lacoste and Romberg gravity meter. The gravity meter does not give an absolute value of the gravity field, but is used to measure the difference relative to a reference point of assumed or known value. A temporary gravity base, set up at Llwynpiod Farm [1780 4770], Cardigan, was assigned a value of 981276.79 mGal, as established by a tie to the fundamental bench mark at Llandovery, the nearest gravity base station of the National Gravity Reference Net, NGRN73 (Masson Smith et al., 1974).

Gravity stations were marked out along each traverse at 25 m intervals using a 100 m tape and spray paint. The first and last gravity stations on the traverse were placed in positions that could be accurately identified on the map; positions of all other stations were marked off at regular intervals from the ends of the line and grid references determined for each station to an accuracy of about 5 m. Gravity stations were located to avoid possible sources of local terrain effect i.e. on firm level ground; no walls or steep topography within a 2 m radius; no drains underneath the road or pavement. Meter drift was monitored on a daily basis by repeat readings at the temporary base station, with additional checks, by re-occupying suitable stations at three to four hour intervals, when gravity surveying.

The traverses were optically levelled with a WILD horizontal level to determine the elevation at each gravity station to a relative accuracy of 1 cm. Where possible, the traverse was levelled in to bench marks or spot heights as a check against gross errors in the surveying and to reference the station elevations relative to OD. Contour heights, as identified from large-scale (1:10 000 to 1:25 000) maps, were used on traverses GT3, GT5 and GT6, where neither bench marks nor spot heights were present.

Gravity data were processed using the software BREDUC (Busby, 1996) with a reduction density of 2.70 Mg/m^3, a standard crustal density as used for generating the Bouguer anomaly maps (Figures 17 and 18). No terrain corrections were applied to the data to allow for differences between the actual ground surface relief and the horizontal slab approximation of the simple Bouguer correction. Variations in terrain effect along the traverses will generally be less than 0.1 mGal and such errors were considered acceptable given other uncertainties relating to the

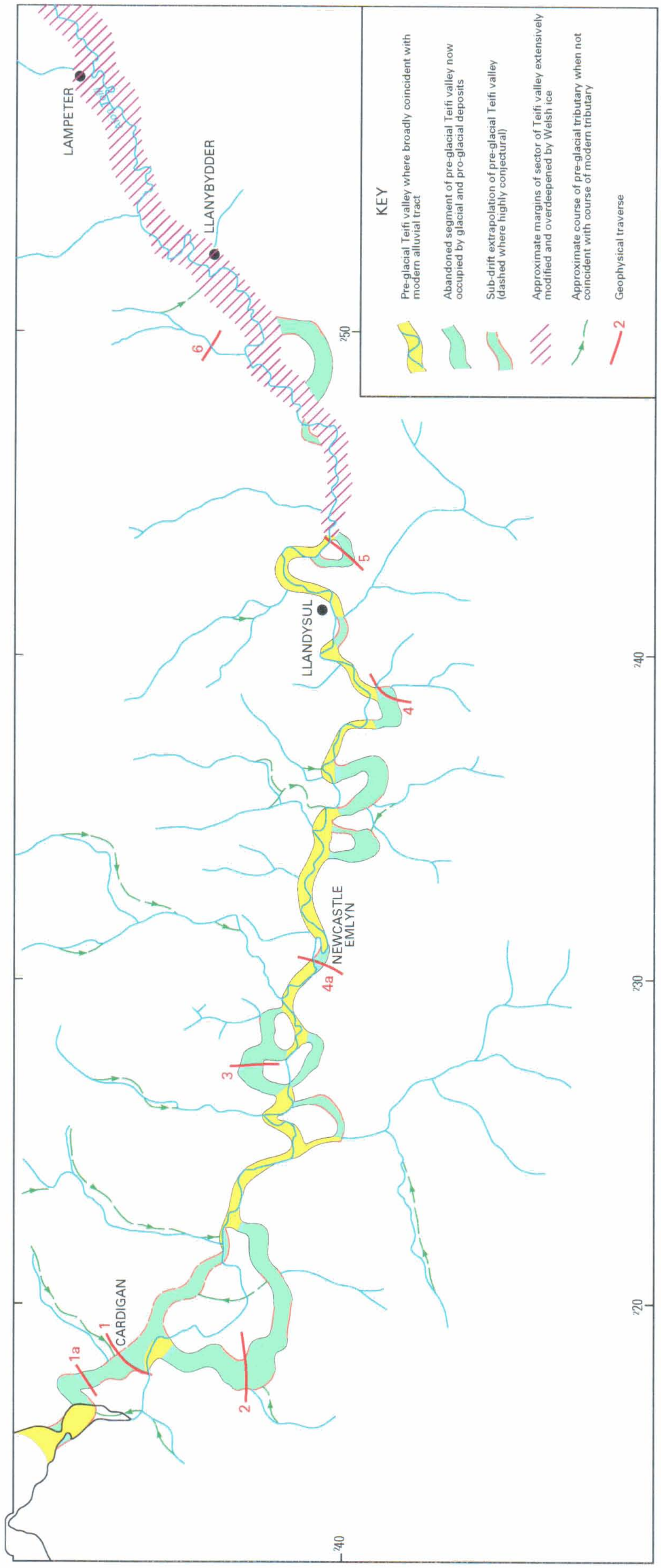


Figure 16 Location of geophysical traverses and buried valleys.

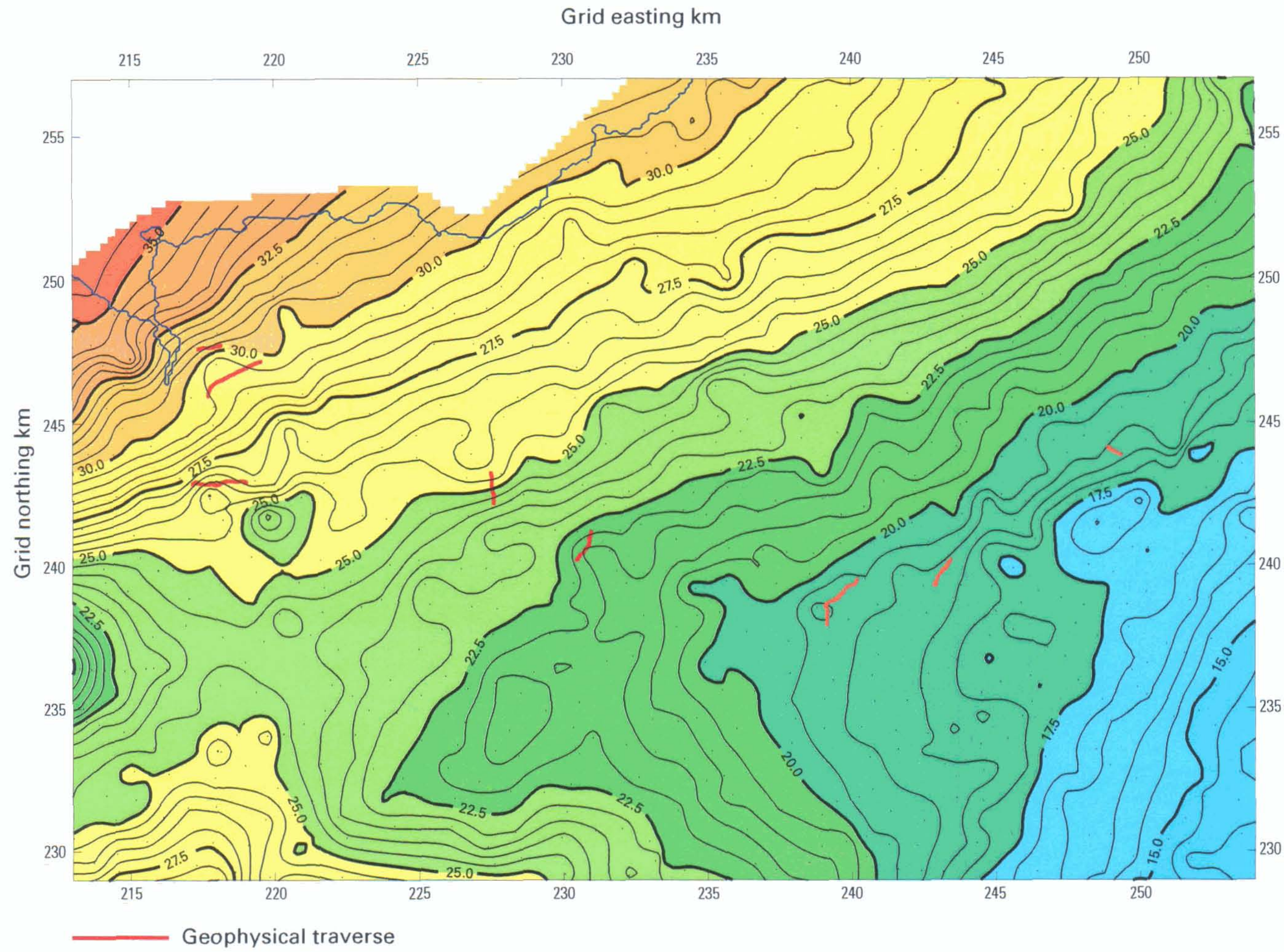


Figure 17 Bouger anomaly contour map of the survey area based on regional gravity stations.

background field and formation densities, and the significant increase in processing time required to correct for terrain effects. However, they will cause some distortion in the interpreted models by being interpreted as part of the subsurface response.

In order to isolate the gravity effect of the buried valley fill, a background field was subtracted from the observed anomaly values, which are in the range 20–30 mGal. In the present case, this background field is intended to account for all effects arising from within the Lower Palaeozoic and underlying rocks. Although the traverses were taken onto shallow bedrock as far as possible, the effective 'zero' level, by which the amplitude of the buried valley anomalies is defined, is not always clear, as some superficial cover of unknown and variable thickness is usually present. The existence of a steep regional gradient across the district (see Figure 17) adds to the difficulty. As an aid to establishing the background field, extended profiles following the alignment of the traverses were extracted from the regional data set for comparison with the observed survey data.

The Bouguer anomaly profiles acquired during this survey were interpreted using the GRAVMAG 2.5D modelling software (Pedley et al., 1993) developed at the BGS. Anomaly values calculated from a series of polygons with defined density values are compared directly with the observed data. The polygons can be constructed to reproduce a realistic, albeit simplified representation of the geology. Adjustments are made interactively to the geometry and densities of the initial model until the required degree of fit is achieved. A background density of 2.75 Mg/m^3, representative of local Lower Palaeozoic bedrock was considered appropriate for the modelling and the observed gravity anomaly values were re-calculated at the same Bouguer reduction density to avoid problems with polygons lying above Ordnance Datum (OD) i.e. effectively mean sea level. The lower density adopted for the regional anomaly map allows for the fact that superficial deposits, weathering effects etc. cause some reduction in the mean density above OD.

Along-line distances were used in constructing the 2D profiles, with no allowance for changes in traverse direction. This will result in the slackening of some local gradients and a slight 'stretching' of the buried valley in the models; the form of the background field will also be distorted. The alternative, of projecting station locations onto a 'best' straight line was not adopted as it produces some anomalously steep, local anomaly gradients and it is not easy to define the best, true sections.

Resistivity

The electrical resistivity technique involves applying a switched direct or low frequency current into the ground using a pair of electrodes. A potential difference is then measured between another pair of electrodes. The measured resistance is multiplied by a geometric factor, which allows for the distances between the current and potential electrodes, to give an apparent resistivity of the

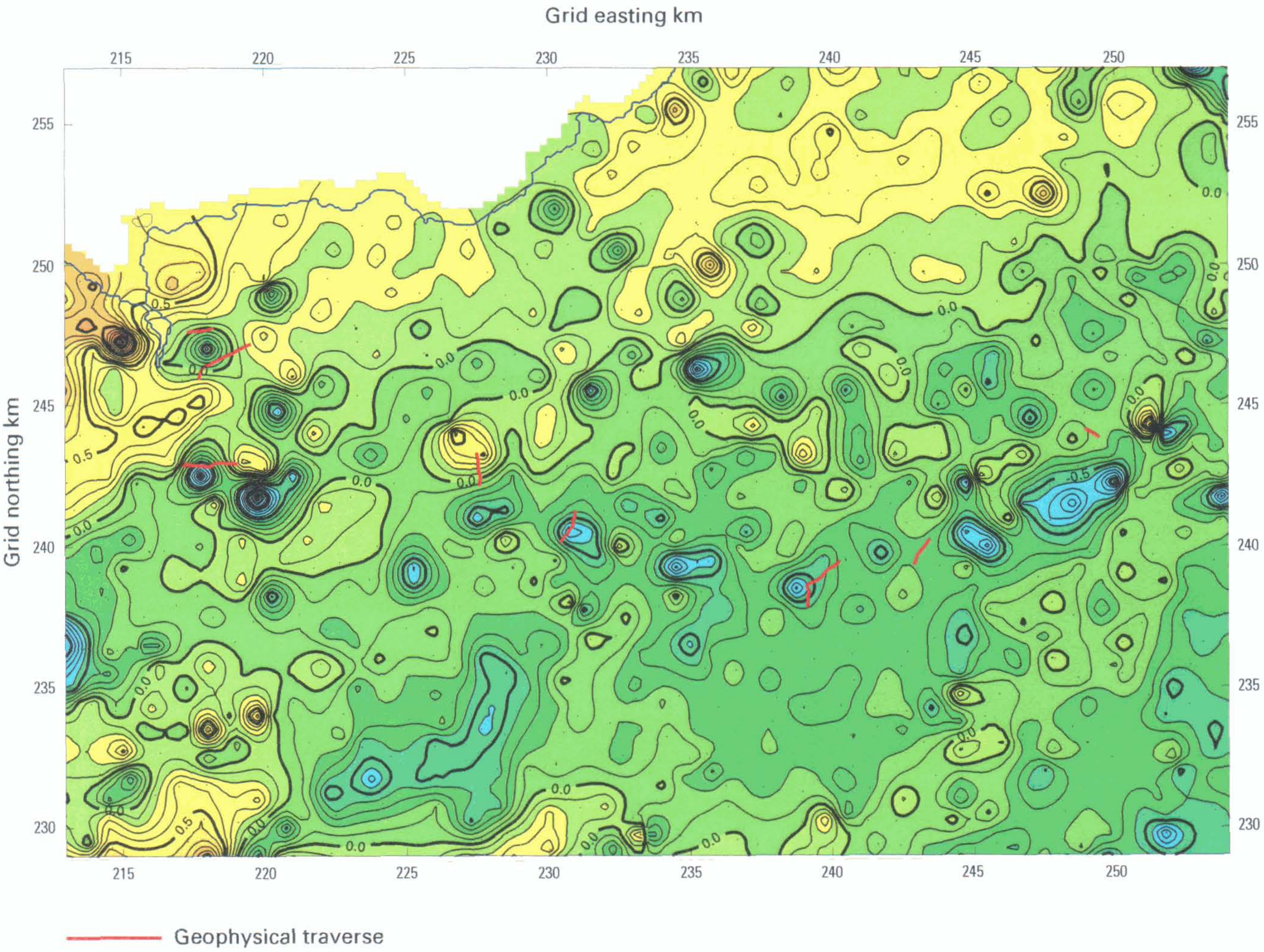


Figure 18 Residual gravity anomaly map (calculated by subtracting 500 m upwardly-continued field from regional data).

ground. This apparent resistivity, which would be the true value if the ground were homogeneous, is a weighted average of the actual resistivities of the materials through which the current passes. By expanding the inter-electrode spacing about a fixed centre, progressively deeper sections of the earth are investigated, thereby yielding a measure of the variation of resistivity with depth. Alternatively, the array can be traversed with a fixed electrode separation to monitor lateral variations.

A limited number of electrode array configurations have been found to be useful for practical surveying (see, for example, Kunetz, 1966; Keller and Frischknecht, 1966 for more information). The Schlumberger array was adopted here in preference to the Wenner array, because it is easier logistically and the data are generally more reliable. The obvious alternative of using the 'offset Wenner' technique in conjunction with a multicore cable was rejected because of the limited number of pre-determined electrode spacings.

In the Schlumberger array, the potential electrodes are separated by a relatively small distance, l m, about the centre point and the current electrodes are located L m either side of this centre (Figure 19a). For the so-called 'depth sounding' survey method, the centre of the array is fixed and L is increased in approximately logarithmic steps to allow for the reducing resolution of the technique; a ratio of 1.25 between successive L values, as adopted in this survey, gives 10 measurements per logarithmic decade (i.e. from between 1 and 10, 10 and 100 etc.). Figure 19b illustrates the way in which the ground contribution to the measured signal varies with distance from the electrodes. The effective depth of investigation varies according to the subsurface conditions: to define an interface and the underlying resistivity reliably, L should be expanded to more than ten times the interface depth, although some indication will be given with a factor of about three.

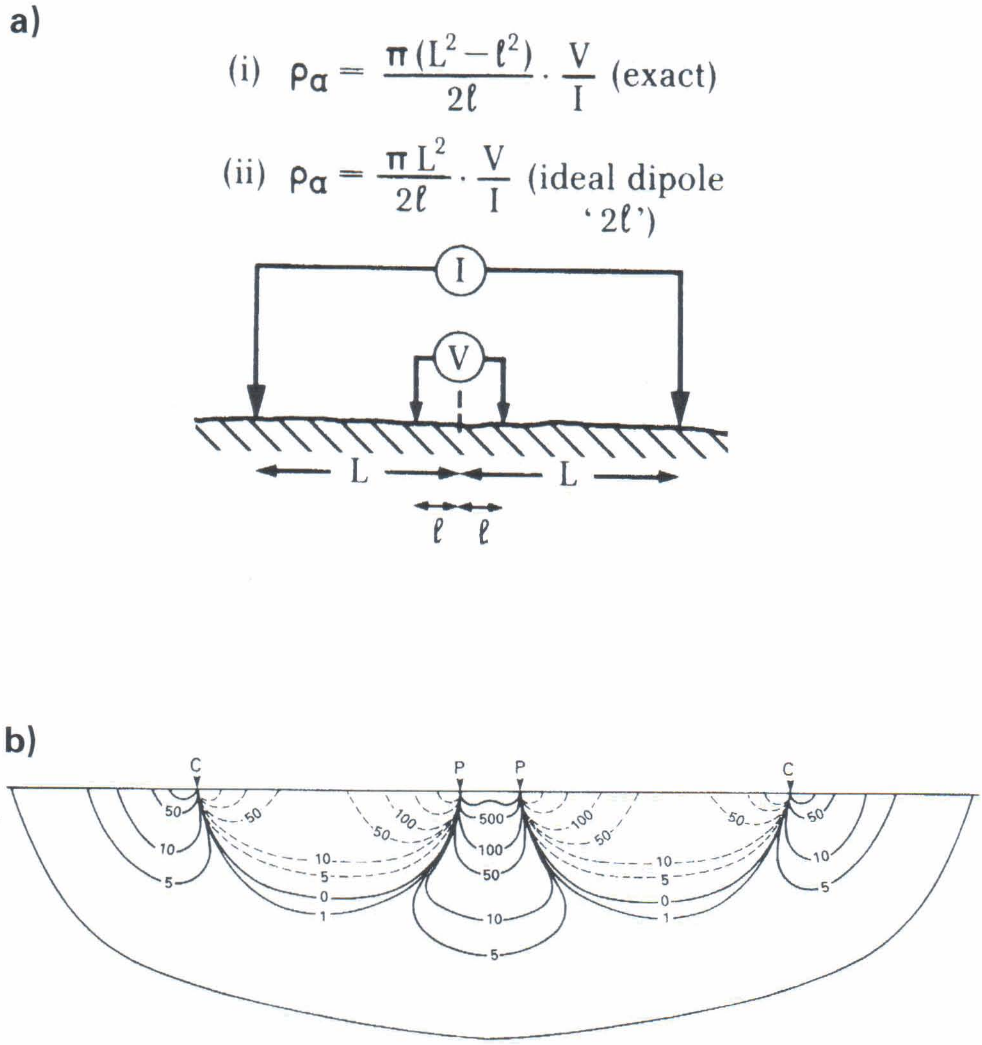
The potential electrodes ideally form a dipole implying that l should remain much less than L (in practice, by a factor of less than 1:5). However, the potential electrode spacing has to be increased occasionally, in order to maintain the accuracy of the voltage measurement. When this is done, at least one repeat measurement is needed with the same current electrode separation, so that adjustments can be made to correct for any lateral variations in ground resistivity. Additional readings give an overlap at the offset which allows the resulting curve segments to be matched more reliably at the processing stage.

From the resistance (i.e. the measured voltage divided by the injected current), an apparent resistivity is calculated for each current electrode position. These values are displayed graphically against the appropriate L spacing to produce a sounding curve, using logarithmic scaling on both axes. Modelling software calculates an equivalent curve for a horizontally stratified earth with specified layer resistivities

Figure 19 Resistivity soundings.

a) The Schlumberger electrode array and its geometric factors used to calculate apparent resistivity (pa) (from Milsom, 1989).

b) Signal contribution section for the Schlumberger array. Contours show the relative contributions to the signal from unit volumes of homogenous ground. Dashed lines indicate negative values (from Milsom, 1989).



and thicknesses, which can be matched directly against the observed values (after adjusting curve segments in the latter to correct for any offsets where the potential electrode spacing changed). Layer properties are changed interactively as necessary to produce an acceptable fit. If marked lateral variations in resistivity occur beneath the electrode array, this simple curve matching process will give incorrect results. There are also limits on the ability to resolve thin layers within the sequence and to differentiate between a range of equivalent resistivity and thickness values for any particular layer. More sophisticated 2D and 3D programs are available but they depend upon having additional input data control.

Measured resistivities at each current and potential electrode spacing were converted to apparent resistivities using the inhouse software program SCHLUM. This also allowed scaling factors to be applied to each section of the curve produced by a different potential electrode spacing so that the sections aligned as a continuous curve. Curve matching by interactive forward modelling was achieved using a separate program, RESPLOT.

As the objective with the resistivity technique was to provide depth estimates at specific points, rather than to indicate the form of the buried valleys qualitatively, the depth sounding (rather than the traversing) mode of operation was adopted. The sounding locations along each traverse were chosen to sample various thicknesses of valley fill sediments, as suggested by the gravity profiles and the geological information regarding buried valleys and shallow bedrock. They were centred at strategic points, as close as possible to the gravity stations, given that the ground needed to be suitable for making electrical contact. Sites in large, flat fields were preferred, with the electrodes aligned perpendicular to the traverse, i.e. along the expected axes of the buried valleys. Ideally, the centre of the sounding would be at a gravity station but this was not always possible as most traverses ran along roads or tracks. In these cases the sounding was sited off-line in an adjacent field. The soundings often had to be continued over field boundaries because individual fields were not large enough for the length of array needed; up to 500 m in places, where the valley fill was thickest.

Survey locations

Gravity data were collected along eight traverses numbered 1, 1a, 2, 3, 4, 4a, 5, 6 (Figure 16) which were planned to cut across the strike of the buried valleys of the Afon Teifi. Large scale plans showing the traverse lines in detail are contained in Carruthers et al. (1997). The aim was to keep each traverse line as straight as possible and to extend well beyond the edges of the buried valley onto shallow bedrock in order to define the background or regional gradient of the gravity field. The length of the traverses varied between 1 and 2 km, making use of roads where possible but taking in tracks and cattle pasture as necessary.

Locations of the gravity traverses and resistivity soundings were finalised in the field to accommodate problems relating to access, man-made sources of interference etc. The fourteen resistivity soundings were distributed between traverses GT1a, 2, 3, 5 and 6. Soundings were not possible on traverses GT1 and GT4a because these ran through built-up areas. On traverse GT4, soundings were not conducted because of time constraints and limited field access, given that the gravity profile indicated only a thin layer of buried valley fill.

INTERPRETATION

Initial assumptions

In modelling both gravity anomaly and resistivity data there is an inherent difficulty in distinguishing between changes in the thickness of a specific layer and in the property value assigned to it. Thus, if there is no control from other sources, such as existing boreholes, the interpretations will only be as good as the assumptions regarding the expected physical properties and the geological sequence.

'Typical' values taken as a starting point for the modelling were based on previous experience of working in this type of terrain, combined with the existing ideas on the geological setting:

Formation	*Density Mg/m³*	*Resistivity ohm.m*
sand and gravel	1.9–2.1	100–500
silts	1.9–2.2	30–70
till	2.1–2.4	50–200
clay	2.1–2.3	10–30
bedrock	2.75	1500

The initial models were generally biased towards lower densities for the superficial deposits so as to indicate the minimum thicknesses to be expected.

Ranges applicable to most of the density and resistivity values are at least 10% and 50% respectively. In particular, the values for unconsolidated material will be influenced by the degree of water saturation, compaction and the effects of varying composition: for example, small (5–10%) amounts of clay can produce a large reduction in the resistivity of sand and gravel, whereas dry gravels can be more resistive than crystalline bedrock; the density of sand and gravel is also dependent on the effective porosity. The density of the Lower Palaeozoic bedrock is not expected to vary by more than 0.05 Mg/m^3, even allowing for a change from mudstone and sandstone dominated facies, although weathering and fracturing may result in a greater reduction locally.

As borehole control becomes available, the property values can be constrained, locally at least, by modelling with fixed interface depths. It is not usually practical to adopt the special procedures needed to obtain density or resistivity measurements on samples taken from unconsolidated sediments, and geophysical logging is usually restricted to gamma readings because of the presence of steel casing.

The interpretation of the gravity and resistivity data went through several iterations. Models were derived independently at first, with only the earlier seismic survey results as a guide to expected depths to bedrock. These were then adjusted to ensure a degree of consistency both between the resistivity and gravity interpretations along each traverse individually and between adjacent traverses. A final revision of all the interpretations was undertaken in the light of the results from the two boreholes (Cardigan No.1 and 2) drilled subsequently. The following sections discuss the results from each traverse, working upstream from the coast. References in the text to positions along the traverses use the notation GT3/550 for a point 550 m from the south(-west) end of traverse GT3; these relate directly to the final model interpretations illustrated in Figures 20 to 27. Resistivity soundings are assigned sequential numbers for each traverse considered independently.

The models presented in this report are essentially geophysical interpretations and they should not be viewed as geological sections in any literal sense. They are also 'over-interpreted' in that the curves have been matched as accurately as possible on the basis of a relatively simplistic initial concept. This provides some insight as to the magnitude of the variations needed to account for the observed variations but, as noted above, there is a wide variety of alternative ways of achieving this match. In practice, the nature of the sequence has been grossly simplified without taking the additional step of inferring a more plausible overall geometry and accepting some discrepancies between observed and calculated anomalies.

Traverse GT1a

This 800 m-long traverse was located 1 km north of Cardigan and close to the present estuary of the Afon Teifi (Figure 16). One of the previous seismic surveys (Allen, 1960) estimated the deepest part of the buried valley to be 33 m below OD on the eastern side of the estuary on a line sited about 1.5 km north-west of GT1a. Of the two resistivity soundings, the first, RS1, was offset some 200 m north of GT1a/300 m along the expected alignment of the buried valley; RS2 was centred near GT1a/510 m.

The gravity anomaly profile (Figure 20), after subtracting a background field, indicates a well defined low extending over a width of about 450 m, with values levelling out at either end where shallow bedrock is expected. The regional gradient, which is relatively constant and shallow to the east, increases significantly at the western end of the traverse; a non-linear change of -0.39 mGal over the length of the traverse was assumed for modelling purposes.

There is no evidence from the gravity data alone that the buried valley fill is not homogeneous and the profile can be matched using a single interface separating valley fill from bedrock. Taking a mean fill density of 2.2 Mg/m^3 gives a maximum depth to bedock of nearly -80 m (relative to OD) and a fill thickness of up to 115 m: by reducing the fill density to 1.9 Mg/m^3 the calculated depth to bedrock rises to no more than 25 m below OD. Although these fits are to within the range of observational error (up to 0.05 mGal if local terrain effects are included) there is some indication of higher anomaly curvatures in the observed data than can be reproduced with this simple type of model.

The resistivity soundings show values falling to less than 25 ohm.m below a more resistive cover. Intermediate layering is suggested by the form of the curves but the precise values and layer thicknesses are poorly defined. At RS1 a layer of 40–45 ohm.m was interpreted to a depth of 20–30 m; this reduced to about 20 ohm.m to a depth of 60–80 m. The latter depth is more uncertain because the end of the sounding curve is steeper than can be accounted for with a horizontally layered earth — as might be expected given the relatively narrow width of the deepest part of the buried valley. These resistivity values strongly suggest glaciolacustrine clays at depth, beneath a more silty or clayey sand-rich sequence, with no evidence of a

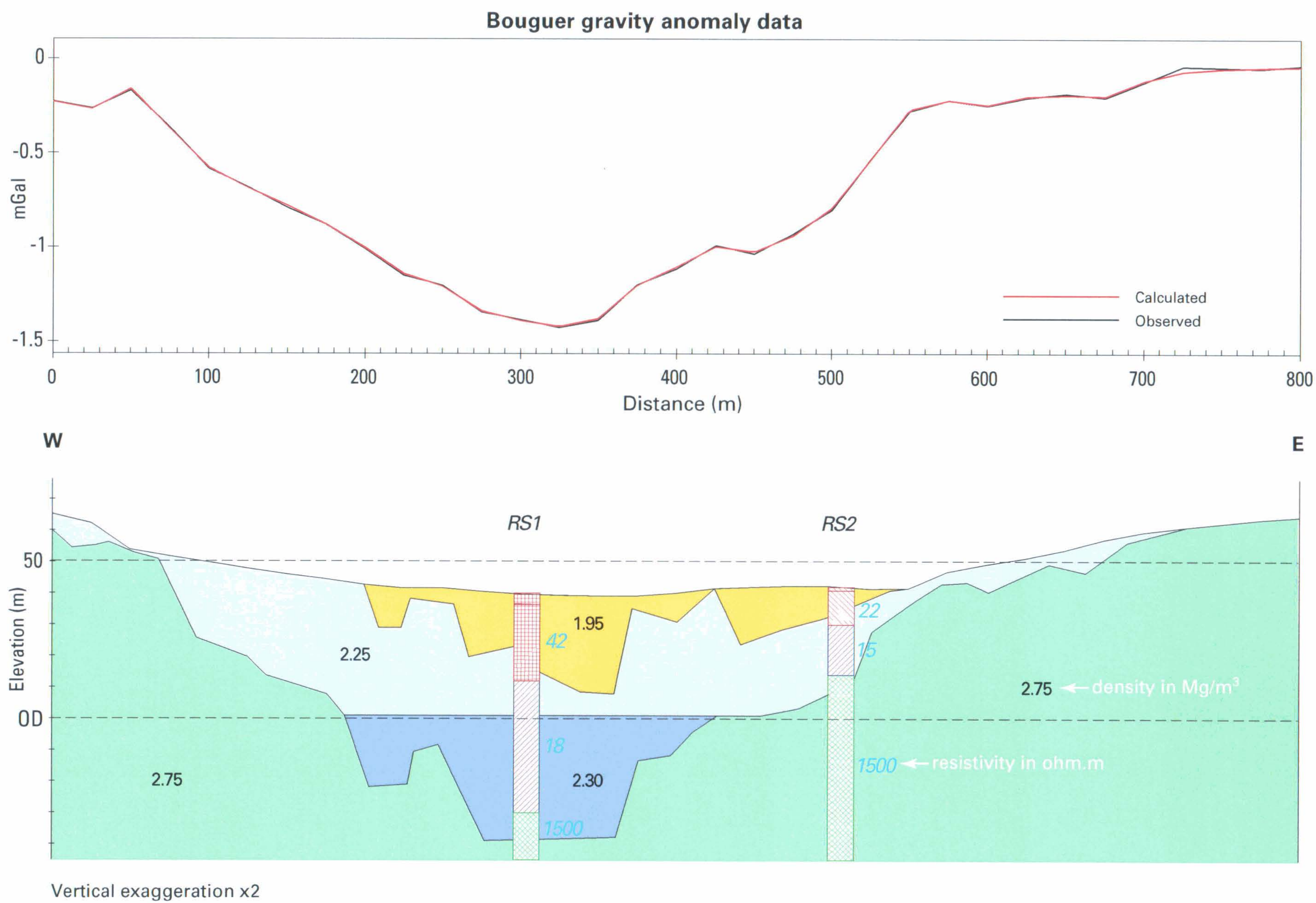


Figure 20 Gravity profile and 2D model with resistivity interpretations for traverse GT1a.

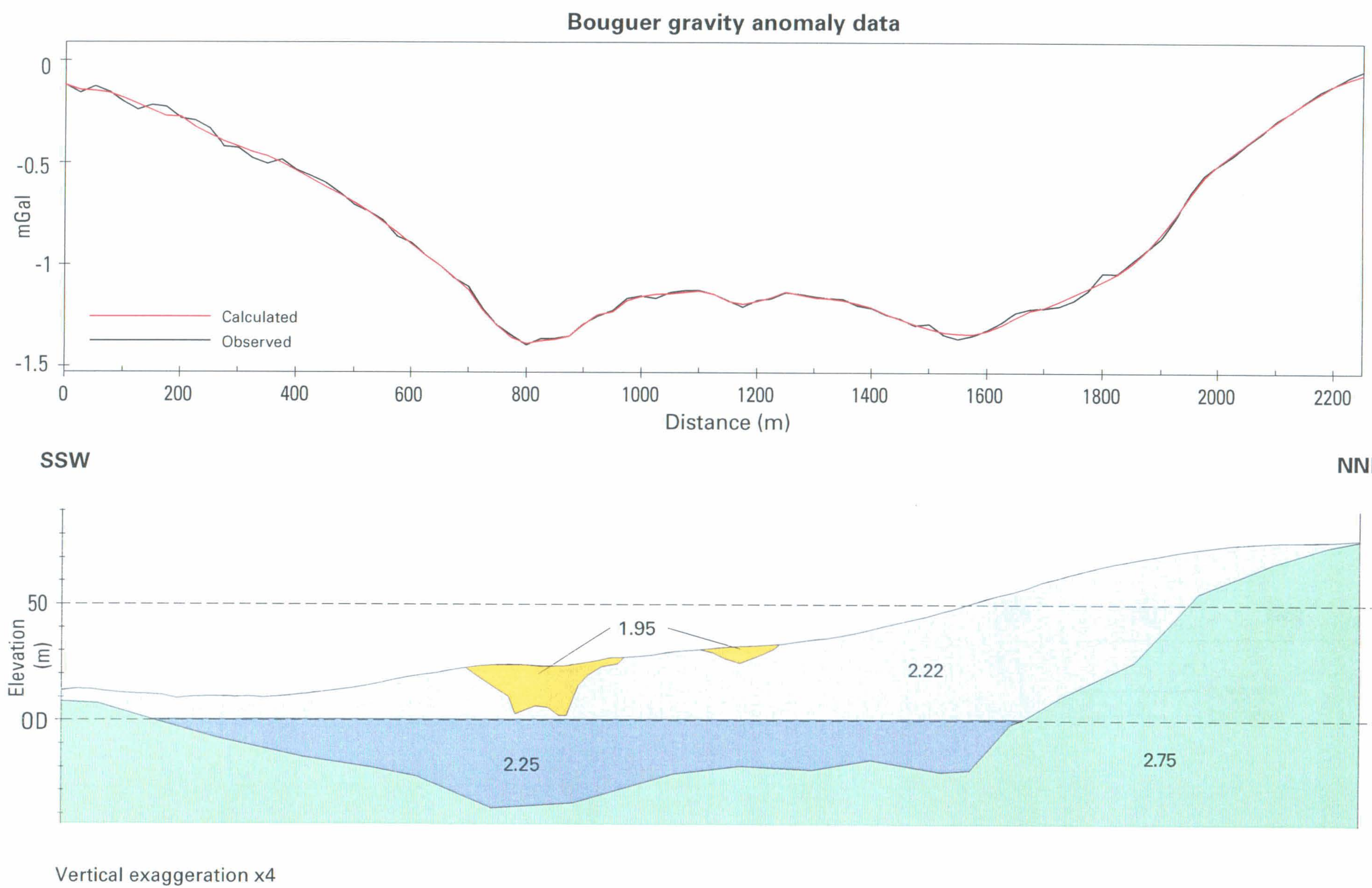


Figure 21 Gravity profile and 2D model for traverse GT1.

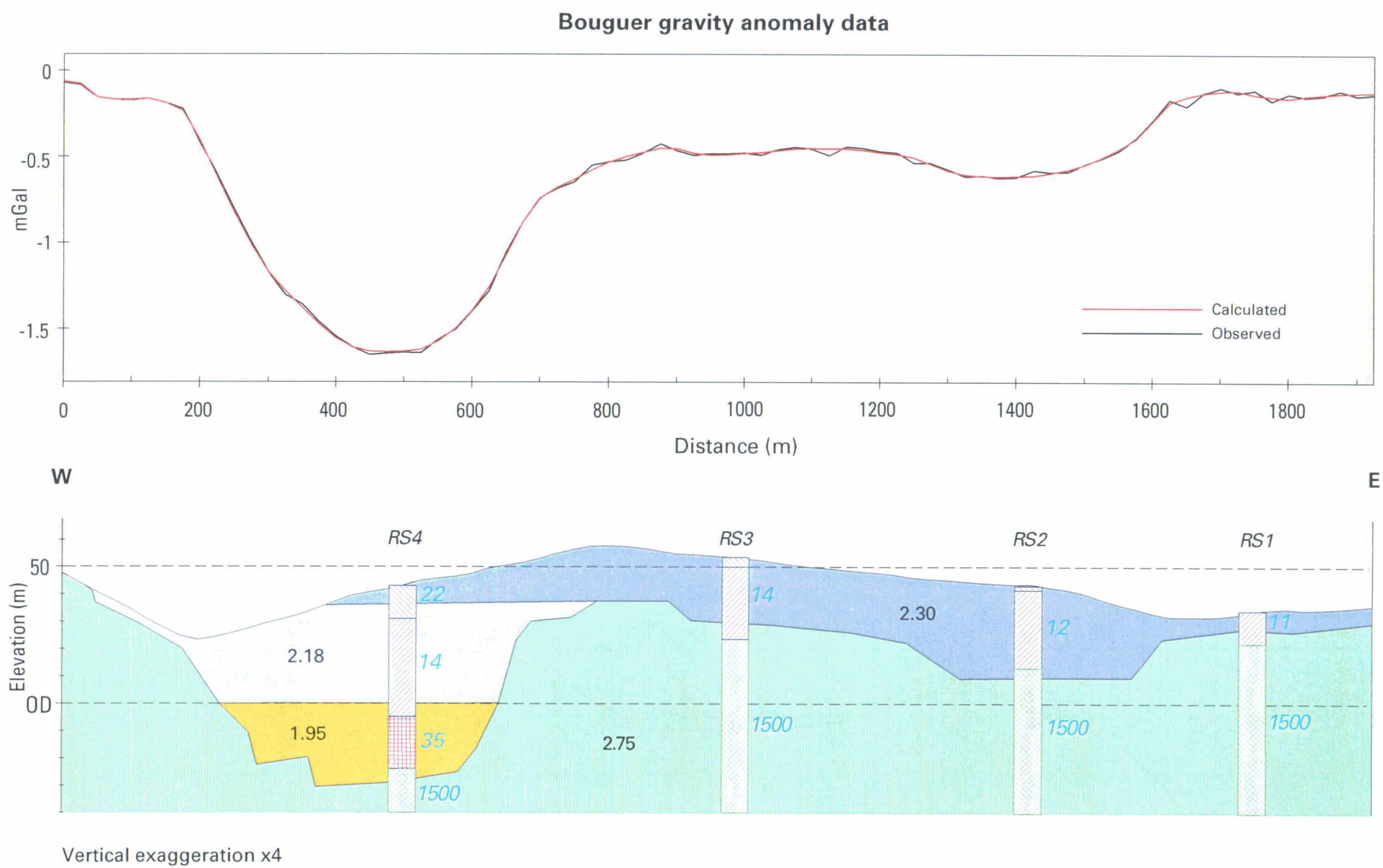


Figure 22 Gravity profile and 2D model with resistivity interpretations for traverse GT2.

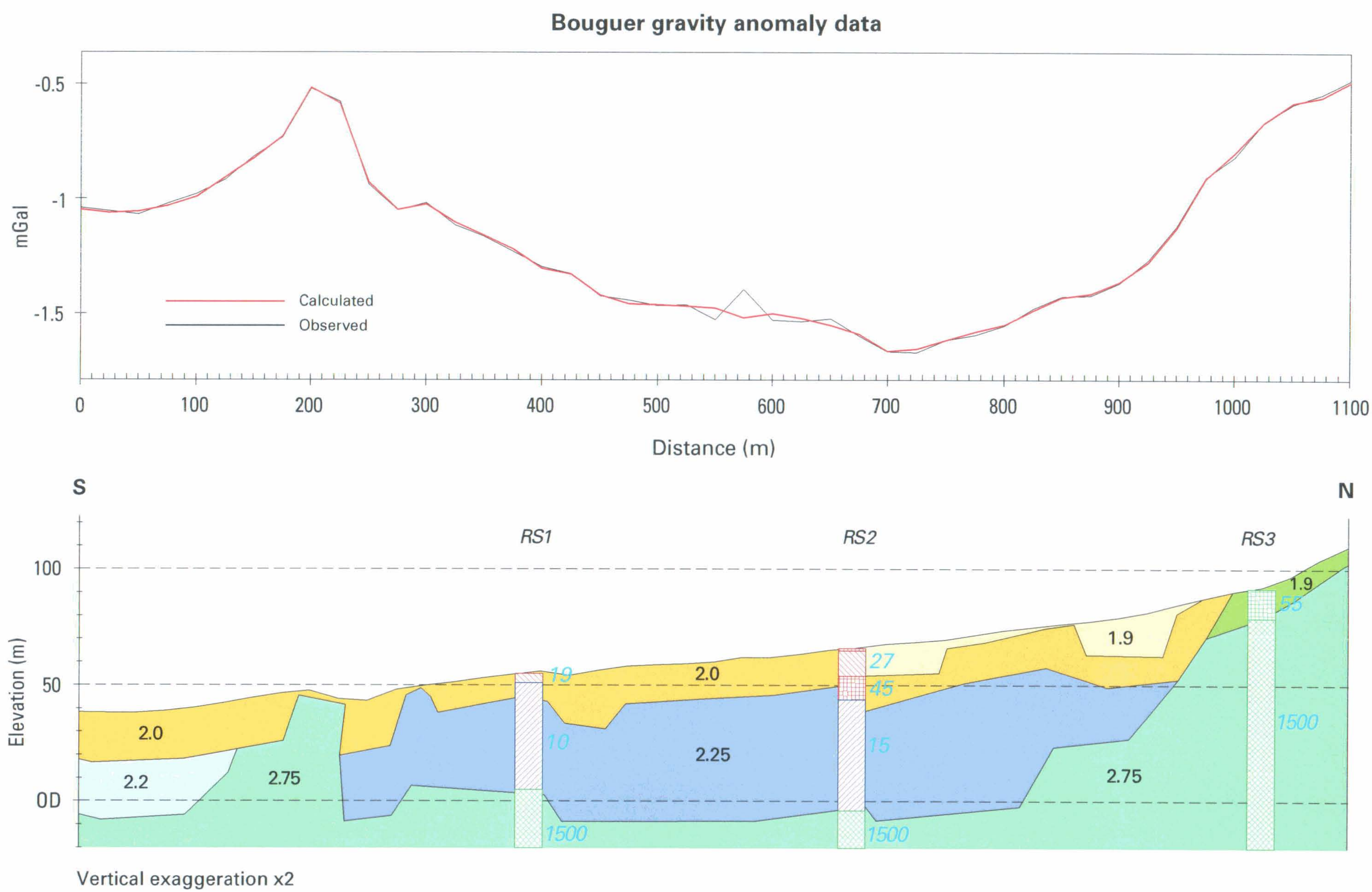


Figure 23 Gravity profile and 2D model with resistivity interpretations for traverse GT3.

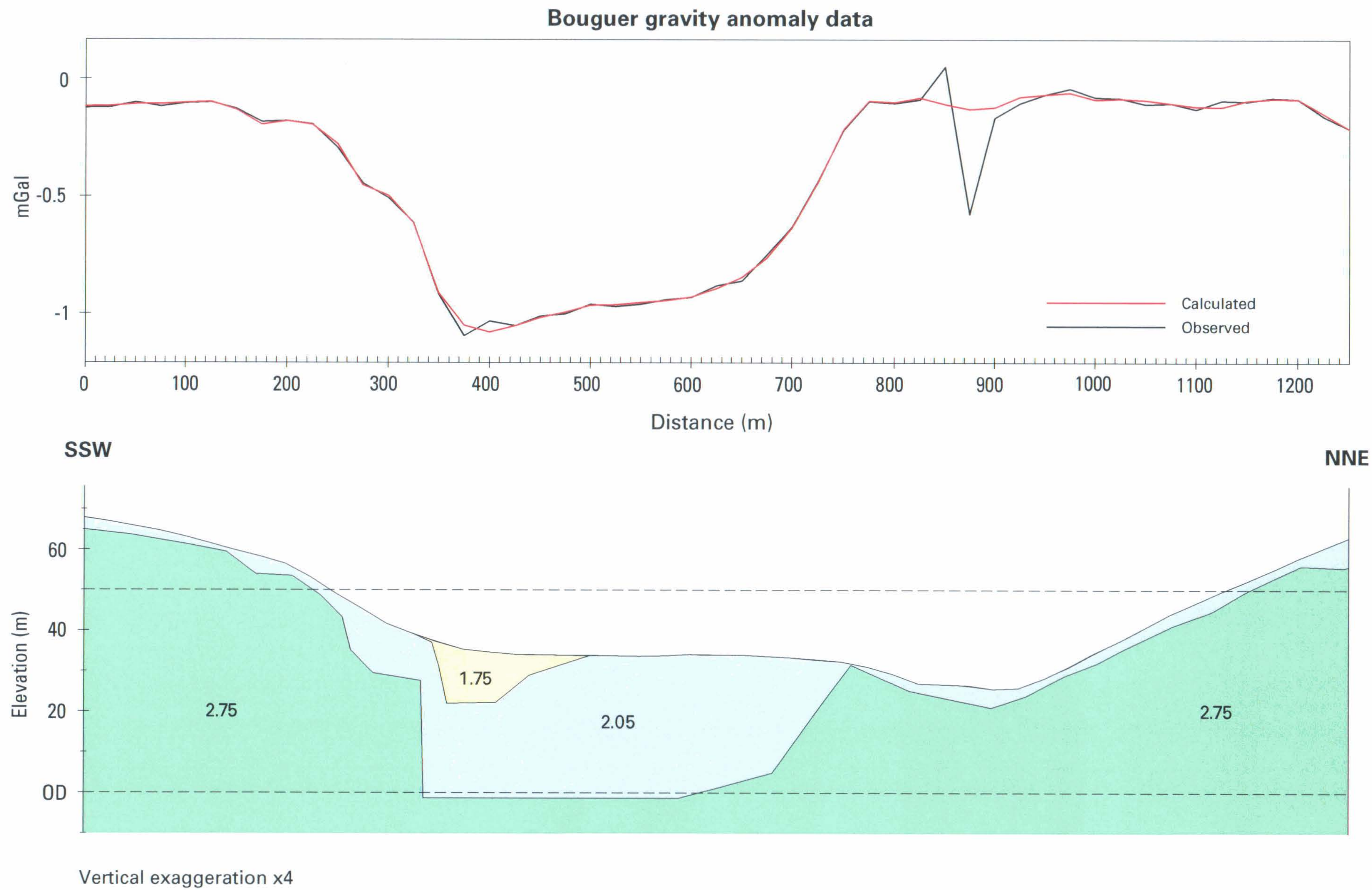


Figure 24 Gravity profile and 2D model for traverse GT4a.

DATABASE OF QUARRIES AND SURFACE MINERAL WORKINGS

Locality Number	Locality Name	Locality Details	Easting	Northing	County	Lithology worked	Surface Lithology (where different)	Solid Formation	Length of Quarry	Width of Quarry	Area of Quarry	State of Activity	Quarried material	Remarks
84	Castle Quarries	S side of Cilgerran Gorge, immediately E of Castle	1958	4310	Pembrokeshire	ROCK		Ntm	110	300	18000	B	Stone	
85	Quarry Forever	SW side of Cilgerran Gorge, 370m WSW of Cwrcoed	1926	4446	Pembrokeshire	ROCK		Ntm	60	40	2200	D	Stone	
86	Chwar Gigfran	SW side of Cilgerran Gorge, 350m WSW of Cwrcoed	1925	4452	Pembrokeshire	ROCK		Ntm	120	85	8000	D	Stone	
87	Quarry Bach	SW side of Cilgerran Gorge, 400m WNW of Cwrcoed	1918	4473	Pembrokeshire	ROCK		Ntm	65	35	1800	D	Stone	
88	Quarry Tommy	SW side of Cilgerran Gorge, 500m WNW of Cwrcoed	1910	4483	Pembrokeshire	ROCK		Ntm	150	140	15500	D	Stone	
89	Quarry Ffynnon	SW side of Cilgerran Gorge, 600m NW of Cwrcoed	1906	4494	Pembrokeshire	ROCK		Ntm	80	65	4200	D	Stone	
90	Quarry Carnarvon	SW side of Cilgerran Gorge, 150m SW of Rose Hill	1902	4500	Pembrokeshire	ROCK		Ntm	140	45	5600	D	Stone	Part of the Forest Quarries. Extends on to SN14SE.
91	Pen-cestyll	Field, 30m NE of Pen-cestyll	1750	4217	Pembrokeshire	GFDUI			60	40	1300	D	S&G	Degraded sand and gravel pit, part of a more extensive area of worked and generally disturbed ground.
92	Waunwhiod	N side of minor road, 300m ENE of Waunwhiod	1477	4528	Pembrokeshire	GFDUI			50	80	3000	D	S&G	Sand and gravel pit with areas of intercalated clayey till.
93	The Moorings	Hillside, 150m ESE of Albro Castle	1617	4667	Pembrokeshire	ROCK		Moy	80	40	2800	D	Stone	

LITHOLOGIES

GDH = Heterogeneous Glacial Deposits Undifferentiated
GFDUI = Glaciofluvial Deposits Undifferentiated (Irish Sea)
GFDUW = Glaciofluvial Deposits Undifferentiated (Welsh)
GFICW = Glaciofluvial Ice-contact Deposits (Welsh)
GFSDW = Glaciofluvial Sheet Deposits (Welsh)
GLLD = Glaciolacustrine Deposits of Lake Teifi

ROCK = Bedrock
RTDU = River Terrace Deposits
TILLI = Till (Irish Sea)

SOLID FORMATIONS

Moy = Moylgrove Group
Ntm = Nantmel Formation
YA = Yr Allt Formation
Cef = Cwmere Formation
Cla = Claerwen Group
Cym = Cwmystwyth Grits Group

WORKINGS

A = active
D = Disused
B = Backfilled

S&G = Sand and Gravel

DATABASE OF QUARRIES AND SURFACE MINERAL WORKINGS

Locality Number	Locality Name	Locality Details	Easting	Northing	County	Lithology worked	Surface Lithology (where different)	Solid Formation	Length of Quarry	Width of Quarry	Area of Quarry	State of Activity	Quarried material	Remarks
65	Allt y Bedw	S side of A484, 150m SW of Dolhaidd Farm	3421	4042	Carmarthenshire	ROCK		Ntm	200	20	2000	B	Stone	Overgrown and partly degraded. Probably used for buildings within Pentrecagal.
66	Pentrecagal	Roadside coppices, 100m to 350m SSE of Greenhill Farm	3396	3999	Carmarthenshire	GLLD			300	90	23000	D	Clay	Irregular area of degraded, overgrown workings. Said to have been used to bulk out coal-dust for low-quality domestic fuel. Contiguous workings on SN34SW.
67	Station Road Pit 2	S side of Station Road (A484), 320m ENE of Pont Pandy.	3183	4061	Carmarthenshire	GFSDW			70	70	4000	B	S&G	Degraded and largely built in sand and gravel pit. Probably one of a contiguous group of pits along roadside.
68	Station Road Pit 1	S side of Station Road (A484), 140m ENE of Pont Pandy.	3167	4052	Carmarthenshire	GFSDW			50	30	1400	B	S&G	Degraded and partly built in sand and gravel pit. Probably one of a contiguous group of pits along roadside.
69	Aber-arad	E side of Afon Arad, 150m SE of Pont Pandy.	3163	4035	Carmarthenshire	ROCK		Ntm	70	35	2000	B	Stone	Overgrown and partly degraded. Probably used for buildings within Newcastle Emlyn.
70	Quarry-ffinant	W side of minor road to Cwmpengraig, 200m SSE of Ebenezer Street (A484).	3081	4019	Carmarthenshire	ROCK		Ntm	60	30	1500	D	Stone	Partly built in. Probably used for buildings within Newcastle Emlyn.
71	Gillo Farm Clay Pits	Coppice, 420m SW of Gillo Farm	2793	4066	Carmarthenshire	GLLD			45	35	1500	D	Clay	Degraded and overgrown.
72	Parcau	Hillside, 250m E of Parcau	2674	4018	Carmarthenshire	ROCK		Ntm	45	35	1500	D	Stone	
73	Cilwendeg	Valley side, 150m ESE of Cilwendeg	2248	3868	Pembrokeshire	ROCK		Ntm	70	40	1800	D	Stone	Probably used in building Cilwendeg mansion and farm.
74	Pentre Farm	Roadside quarry, 270m WNW of Pentre Farm	2285	4103	Pembrokeshire	ROCK		Ntm	50	50	2500	D	Stone	Overgrown. Probably used in building of farm and mansion.
75	The Belt	Hilltop, 700m NW of Pentre Mansion and 250m W of plantation ('The Belt)	2260	4137	Pembrokeshire	ROCK		Ntm	90	55	3500	D	Stone	Shallow, interconnected workings, partly overgrown.
76	Castle Malgwyn Farm 2	350m NNE of Castle Malgwyn Farm	2230	4338	Pembrokeshire	GFDUI			75	40	1700	D	S&G	degraded sand and gravel pit ? for local use.
77	Castle Malgwyn Farm 1	Immediately SW of Castle Malgwyn Farm	2213	4300	Pembrokeshire	ROCK		Ntm	50	35	1500	D	Stone	Probably used in building of farm.
78	Penralltcadwgan	Field, 250m NE of Penralltcadwgan	1922	4086	Pembrokeshire	GFDUI			55	35	1800	A	S&G	
79	Ty-hen	Valley side (E), 120m E of Ty-hen	1905	4087	Pembrokeshire	ROCK		Ntm	45	30	1200	D	Stone	
80	Cefn Quarries	S side of Cilgerran Gorge, immediately N and W of Brynsiriol	2064	4298	Pembrokeshire	ROCK		Ntm	60	450	27000	D	Stone	Part of a contiguous set of quarries along the south side of the Cilgerran Gorge.
81	Plain Quarry	S side of Cilgerran Gorge, 300m WSW of Brynsiriol	2040	4286	Pembrokeshire	ROCK		Ntm	90	60	7500	D	Stone	Part of a contiguous set of quarries along the south side of the Cilgerran Gorge.
82	Pwdwr Quarry	SW side of Cilgerran Gorge, 280m ENE of Chapel	1995	4287	Pembrokeshire	ROCK		Ntm	150	75	7000	D	Stone	Extends on to SN24SW.
83	Cilgerran Quarry	S side of Cilgerran Gorge, immaedately adjacent to car park	1980	4295	Pembrokeshire	ROCK		Ntm	60	20	1000	D	Stone	

DATABASE OF QUARRIES AND SURFACE MINERAL WORKINGS

Locality Number	Locality Name	Locality Details	Easting	Northing	County	Lithology worked	Surface Lithology (where different)	Solid Formation	Length of Quarry	Width of Quarry	Area of Quarry	State of Activity	Quarried material	Remarks
42	Llandysul 2	N side of Afon Teifi, 250m WSW of bridge	4116	4020	Ceredigion	ROCK		YA	70	30	2000	D	Stone	
43	Llandysul 1	W side of B4476, on 300m N of Church	4190	4100	Ceredigion	ROCK		YA	70	35	2000	D	Stone	Partly built in.
44	Bryn Teifi	N side of minor road to Capel Dewi, 250m SW of Faerdre Fawr	4256	4202	Ceredigion	GFDUW			40	30	1000	D	S&G	Degraded sand and gravel pit, partly excavated into landslip.
45	Allt Cilgraig	Adjacent to track on hillside,100m N of Broneinon Mill	4551	4287	Ceredigion	ROCK		YA	70	20	1200	D	Stone	
46	Fronfelen	Hillside, 110m NW of Fronfelen	4553	4111	Ceredigion	ROCK		YA	75	60	4200	D	Stone	
47	Gerynant	NW side of Afon Teifi, 200m ENE of Gerynant	5166	4419	Ceredigion	GFICW			60	70	4000	D	S&G	
48	Goedwig	NW side of A475, 400m W of Peterwell	5664	4776	Ceredigion	GFICW			50	30	1200	D	S&G	
49	Ger y Fro	N side of A482, immediately behind Depot	5753	4894	Ceredigion	GFICW			170	60	8500	B	S&G	Partly built in.
50	Cwm-Rhys	Hillside,150m ESE of Cwm-Rhys	5844	4874	Ceredigion	ROCK		Cla	120	90	9000	D	Stone	
51	Lampeter Station 1	Valley side (E), 200m SE of St David's College buildings	5810	4810	Ceredigion	GFSDW			100	40	2500	B	S&G	
52	Lampeter Station 2	Valley side (E), 300m SSe of St David's College buildings	5812	4802	Carmarthenshire	GFSDW			65	30	1600	D	S&G	
53	Tanlan	Hillside below plantation, 80m SE of Tanlan	5792	4644	Carmarthenshire	ROCK		Cla	50	40	1800	A	Stone	
54	Tan-y-foel	E side of A482, 110m SW of Tan-y-foel	5867	4609	Carmarthenshire	ROCK		Cym	55	45	1600	D	Stone	
55	Coedeiddig Fawr	Adjacent to A482, on E side opposite Chapel	5862	4603	Carmarthenshire	ROCK		Cym	120	80	7500	D	Stone	
56	Gery-lyn	Hillside, 70m ESE of Gery-lyn	5402	4553	Carmarthenshire	ROCK		Cla	65	40	3000	D	Stone	
57	Glantren Wood	SE side of A485, 280m NW of Glantrenfawr	5193	4322	Carmarthenshire	ROCK		Cla	50	40	2500	D	Stone	
58	Manor Hotel Quarry	Hillside, 170m SSW of Manor Hotel	4773	4032	Carmarthenshire	ROCK		CeF/ YA	60	20	1200	A	Stone	
59	Allt Cross-Inn-fach	Woodland, 600m WSW of Llanfihangel-ar-arth Church	4503	3970	Carmarthenshire	ROCK		YA	85	20	1500	D	Stone	
60	Plyg-y-rhiw	Immediately SE of plyg-y-rhiw	4173	3995	Carmarthenshire	ROCK		YA	60	20	1000	D	Stone	Partly built in and degraded.
61	Plas-Geler	W side of Teifi valley, 110m NNE of Plas-Geler	3774	3945	Carmarthenshire	ROCK		Ntm	50	25	1000	D	Stone	
62	Temple Cottage	Hillside between minor roads, 100m SSE of Temple Cottage	3552	3796	Carmarthenshire	ROCK		Ntm	60	30	2000	D	Stone	
63	Cwmpencraig	Immediately E of minor road, 230m NNW of Bach y Gwyddel	3501	3680	Carmarthenshire	ROCK		Ntm	70	30	2000	D	Stone	
64	Bargod	Meadows, 250m N of Pont Bargod	3507	4038	Carmarthenshire	RTDU			65	60	3000	D	S&G	Degraded and flooded gravel pit.

DATABASE OF QUARRIES AND SURFACE MINERAL WORKINGS

Locality Number	Locality Name	Locality Details	Easting	Northing	County	Lithology worked	Surface Lithology (where different)	Solid Formation	Length of Quarry	Width of Quarry	Area of Quarry	State of Activity	Quarried material	Remarks
22	Allt Pant-gwyn	Valley side (W), 160m SSW of Parctwad	2354	4527	Ceredigion	ROCK		Ntm	40	30	1000	D	Stone	
23	Blaeneifed	Hillside, 300m ESE of Blaeneifed	2435	4555	Ceredigion	ROCK		Ntm	50	50	2000	D	Stone	
24	Cringae-newydd	Field, 100m NE of Cringae-newydd	2525	4835	Ceredigion	ROCK		Ntm	110	50	3000	D	Stone	
25	Noyadd Trefawr	E side of minor road, immediately W of Noyadd Trefawr	2579	4625	Ceredigion	ROCK		Ntm	120	20	2000	D	Stone	Group of small contiguous quarries.
26	Nantgwgan	Head of small valley, 100m S of Nantgwgan	2641	4455	Ceredigion	ROCK		Ntm	75	25	1500	D	Stone	
27	Cilfallen	E side of minor road, 180m SW of Cilfallen	2959	4303	Ceredigion	ROCK		Ntm	40	35	1500	D	Stone	
28	Plas Troedyraur	S side of minor road, 230m S of Plas Troedyraur	2978	4588	Ceredigion	ROCK		Ntm	75	35	2300	D	Stone	
29	Cwmcoednerth	Trackside, 70m SW of Cwmcoednerth	3435	4835	Ceredigion	ROCK		Ntm	130	15	1800	D	Stone	
30	Gwernant Home Farm	Immediately N of Gwernant Home Farm	3363	4618	Ceredigion	ROCK		Ntm	110	50	3500	D	Stone	Probably used in building of farm
31	Troedyraur	Roadside, 400m SW of St. Michael's Church	3295	4505	Ceredigion	ROCK		Ntm	60	30	1500	D	Stone	
32	Brickfield Covert	Coppice, 370m NNW of Penwalk.	3114	4242	Ceredigion	GLLD			100	90	9500	D	Clay	Irregular area of degraded workings. Probably used for bricks, or as bulking agent for low-quality fuel (coal-dust) as at Pentrecagal (see SN33NW01).
33	Allt y Fedw	Woodland, 300m WSW of Brickfield Covert.	3087	4227	Ceredigion	ROCK		Ntm	150	20	1500	D	Stone	Overgrown.
34	Cwr-coed	NE side of B4833, 850m NW of Newcastle Emlyn bridge.	3037	4150	Ceredigion	GLLD			130	60	6000	B	Clay	Excavated landslipped material, mostly used as fill in/near Newcastle Emlyn, but also to cap landfill and as liner for lagoon at oil refinery.
35	Adpar	Old pheasantry, 250m NW of Cilgwyn.	3103	4117	Ceredigion	GFDUW			40	40	1600	D	S&G	Overgrown and degraded sand and gravel pit.
36	Allt Cwm-erllys	Valley side (E), 400m SE of Old Cilgwyn.	3189	4152	Ceredigion	ROCK		Ntm	50	40	2000	B	Stone	Overgrown.
37	Dolau	Immediately E of Dolau farm buildings.	3332	4136	Ceredigion	ROCK		Ntm	40	30	1100	D	Stone	Partly built in.
38	Pwll-cornel-uchaf	Adjacent to track, 350m NE of Pwll-cornel-uchaf	3740	4307	Ceredigion	ROCK		YA	180	25	3000	D	Stone	Comprises two narrow, contiguous quarries, on either side of track.
39	Aberhoffnant	Hillside, 50m SW of Aberhoffnant	3941	4019	Ceredigion	ROCK		YA	35	35	2500	D	Stone	
40	Troedrhiwffenyd	S side of A475, 250m NW of Troedrhiwffenyd	4077	4274	Ceredigion	GFICW			70	40	2500	B	S&G	Degraded sand and gravel pit with solid in back face. Planned extension of site towards Pentrellwyn refused.
41	Allt Gorrig	N side of minor road, 300m W of Gorrig crossroads	4082	4294	Ceredigion	ROCK		YA	60	35	1500	D	Stone	Overgrown quarry in well bedded sandstone, said to have been used in buildings around Pentrellwyn.

DATABASE OF QUARRIES AND SURFACE MINERAL WORKINGS

Locality Number	Locality Name	Locality Details	Easting	Northing	County	Lithology worked	Surface Lithology (where different)	Solid Formation	Length of Quarry	Width of Quarry	Area of Quarry	State of Activity	Quarried material	Remarks
1	Manian Fawr	N side of track, 180m W of Manian-fawr	1508	4793	Ceredigion	ROCK		Ntm	50	20	1000	D	Stone	
2	Trwyn-yr-allt	Immediately SE of Trwyn-yr-allt	1737	4802	Ceredigion	ROCK		Ntm	40	40	1200	D	Stone	Currently occupied by coal merchant's yard.
3	Cardigan Brick Pit	250m WSW of Cardigan Secondary School	1790	4654	Ceredigion	GLLD	TILLI		300	150	31000	B	Clay	with glaciofluvial sands in eastern face. Main brick pit of Cardigan.
4	King George's Field Clay Pit	S end of playing fields, 100m SE of Rugby Clubhouse	1832	4659	Ceredigion	GLLD	TILLI		60	30	1500	B	Clay	Series of irregular workings in Glaciolacustrine Clay.
5	Cwmdegwel	SE side of minor road, 250m NNW of Cefn	1639	4549	Ceredigion	ROCK		Moy	100	25	2000	D	Stone	Quarry in steeply dipping well-bedded sandstones.
6	Bryngwyn	Small valley, 150m NNW of Hendy	1706	4520	Ceredigion	ROCK		Ntm	120	35	3600	D	Stone	Excavation along rock gorge.
7	Gamallt	Trackside, immediately NW of Gamallt	1630	4439	Ceredigion	ROCK		Ntm	200	45	8000	B	Stone	Series of interconnected excavations, now disused but containing a concrete mixing plant.
8	Gallt y Cwarel	Hillside, 80m S of Rising Sun	1786	4451	Ceredigion	ROCK		Ntm	40	40	1200	D	Stone	
9	Pentood	Between A487(T) and Cardigan By-pass, 150m SSW of Pentood roundabout	1799	4518	Ceredigion	ROCK		Ntm	60	30	1000	D	Stone	
10	Felin Fach	Valley side (N), 50m NE of Felin Fach	2035	4926	Ceredigion	ROCK		Ntm	70	20	2000	D	Stone	
11	Penparc	1km WNW of Penparc Post Office	2018	4844	Ceredigion	GFDUI			900	400	250000	A	S&G	Extends onto SN14NE. Formerly worked as two pits, the Upper and Lower Pits.
12	Cilmaenllwyd	700m NW of Penparc Post Office	2044	4831	Ceredigion	GFDUI			120	280	28000	B	S&G	Former landfill site, now in use as waste recycling/repackaging plant.
13	Pant-y-dwr	Fields, 410m NW of Penparc Post Office.	2086	4825	Ceredigion	GFDUI			50	40	1400	D	S&G	
14	Crug-du-isaf	Hilltop, 150m ENE of Warren Farm	2033	4771	Ceredigion	GFDUI			50	50	2500	D	S&G	
15	Banc-y-Warren	Hillside, 150m SE of Warren Farm	2031	4750	Ceredigion	GFDUI			40	30	1000	A	S&G	
16	Bronydd	Head of small valley, 350m SSE of Bronydd	2188	4557	Ceredigion	ROCK		Ntm	50	20	1000	D	Stone	
17	Pencraig	Woodland, 100m S of Pencraig	2229	4608	Ceredigion	ROCK		Ntm	30	25	1000	D	Stone	Area of contiguous small workings.
18	Llechryd Sewage Works	Woodland, 100m SSW of Llechryd Sewage works	2111	4355	Ceredigion	GFDUI			50	100	5000	D	S&G	Overgrown and degraded sand and gravel pit.
19	Llechryd Pit	Woodland, 50m NE of sewage works	2121	4370	Ceredigion	GFDUI			65	30	1800	D	S&G	Overgrown and degraded sand and gravel pit. Silt and clay in back face
20	Teg-fan	S side of B4570, 350m WSW of Teg-fan	2259	4504	Ceredigion	GDH		Ntm	60	30	1000	B	S&G	Degraded quarry, probably formerly worked for sand and gravel or stone.
21	Nant Eifed	Valley side (E), 350m SSW of Parctwad	2355	4505	Ceredigion	ROCK		Ntm	60	50	1200	D	Stone	

CL, CI, CH (low to high plasticity clay)
Sandy silty GRAVEL

Head (HEAD)
Soliflucted, slopewash material (content dependent on source deposit)
Heterogeneous
CL, CI, MI (low to intermediate plasticity)
Well-graded clayey SILT/SAND/GRAVEL + cobbles

Glacial and glaciolacustrine deposits, undifferentiated, (Irish Sea) (GGLDI)
CL, CI, CH (low to high plasticity clay)
Clayey sandy SILT and silty CLAY

Older alluvium (OAL)
Slightly silty sandy GRAVEL + cobbles

Alluvium (ALV)
Heterogeneous. Some cementing. Clay-rich component not represented in database.
CI, MI, MH (intermediate to high plasticity)
Well-graded slightly silty sandy GRAVEL + cobbles and poorly-graded gravelly SAND

Tidal river deposits (TRD)
Organic muds + subordinate coarse grade
Soft to stiff, (strength decreasing with depth)
CI, MI, MH, MV (intermediate to very high plasticity)
Well-graded sandy GRAVEL + cobbles and sandy SILT

NON-COHESIVE SOILS

Glaciofluvial Deposits, Undifferentiated (Irish Sea) (GFDUI)
Gravelly SAND and slightly sandy GRAVEL + cobbles

MAN-MADE DEPOSITS

Made ground (MGR)
Heterogeneous
CL (low plasticity)
Well-graded SILT/SAND/GRAVEL

SOLID ROCKS

Moylgrove Group (Moy)
Non-plastic
Slightly sandy medium to coarse GRAVEL

Nantmel Mudstones Formation (Ntm)
CL (low plasticity clay) (probably weathered samples)
Well-graded sandy GRAVEL and gravelly fine SAND

Limitations of data

With the exception of the standard penetration test data, all data are derived from selected laboratory test samples, which are very small compared with the mass of soil or rock. In the case of strength data from uniaxial or triaxial tests, these are usually obtained from 'intact' specimens, which do not have representative discontinuities within them.

It should be noted that for the geological units with few geotechnical data, there is a likelihood that some lithological component has not been tested. For example, the clay-rich component of the alluvium is not represented in the database. This applies also to glacially derived deposits where a clay-rich layer, though unrepresentative of the whole formation, may play a significant role in an engineering situation. An example of this is the stability of an excavation which may be adversely affected by a relatively minor clay-rich band. Similarly, a formation described as 'non-cohesive' may contain isolated cohesive material.

It should also be noted that the geotechnical information presented here should not be used to provide design parameters or as a substitute for a proper site investigation. The quality of the data used, whilst having been assessed as far as possible, cannot be vouched for.

Figure 38 e–g
Statistical data

e plastic limit
f natural moisture content
g pH.

e)

Plastic Limit

	All	GLLD	TILLI	HEG	HEAD	GGLDI	TRD	MGR	Ntm
Samples	176	43	39	18	13	9	24	13	5
Min	12	14	12	15	14	15	19	17	14
2.5	14								
10	16	16	15						
25	19	18	17	19	18		22	20	
50	**22**	**22**	**19**	**21**	**19**	**24**	**27**	**21**	**19**
75	26	27	24	24	24		33	25	
90	31	30	26						
97.5	42								
Max	62	35	31	31	35	31	62	42	20

f)

Natural Moisture Content

	All	GLLD	TILLI	HEG	HEAD	GGLDI	ALV	TRD	GFDUI	MGR	Ntm
Samples	289	91	58	30	18	12	7	26	5	23	8
Min	3	11	6	8	4	17	12	20	4	4	4
2.5	6										
10	10	19	15	11				23			
25	16	24	16	15	11	20		28		9	
50	**21**	**32**	**19**	**18**	**16**	**23**	**29**	**34**	**8**	**13**	**8**
75	32	37	22	24	20	26		48		23	
90	38	41	26	31				63			
97.5	48										
Max	75	48	37	35	32	34	40	75	18	70	17

g)

pH

	All	TILLI	HEAD	ALV	TRD	GFDUI	MGR	Moy
Samples	94	13	10	12	14	7	9	8
Min	4.5	6.8	5.9	6.0	5.0	4.8	5.9	4.5
10	5.9							
25	6.8	7.2	6.4	6.9	7.4			
50	**7.4**	**7.4**	**7.3**	**7.2**	**7.7**	**6.3**	**7.5**	**6.9**
75	7.7	7.6	7.4	7.5	7.8			
90	8.0							
Max	8.7	8.4	8.0	8.2	8.6	7.6	8.2	7.5

Summary description of geological units in the geotechnical database:

COHESIVE SOILS

Glaciolacustrine Deposits, Lake Teifi (GLLD)

Grey and brown varved clays and silts with interbeds of silt and fine sand, + dropstones.
Soft to very stiff (slight decrease in strength with depth)
CL, CI, CH (low to high plasticity clay)
Sandy silty CLAY, silty CLAY, and clayey sandy SILT

MIXED COHESIVE/NON-COHESIVE SOILS

Till (Irish Sea) (TILLI)

Red-brown clays, cryoturbated sand/silt beds + cobbles + boulders
Firm to stiff (little change in strength with depth)
CL, CI, CH (low to high plasticity clay)
Well-graded sandy silty CLAY, sandy gravelly SILT, and poorly-graded silty coarse SAND/GRAVEL

Head gravel (HEG)

Weathered rock debris, mudstone clasts
Soft to stiff

a)

Bulk Density	All	GLLD	TILLI	HEG	HEAD	GGLDI	TRD	Moy
Samples	105	22	36	13	8	5	6	7
Min	1.66	1.89	1.84	1.81	1.83	2.02	1.66	2.36
2.5	1.79							
10	1.91		1.97					
25	1.99	1.97	2.02	1.91				
50	**2.07**	**2.02**	**2.08**	**1.97**	**2.10**	**2.09**	**1.84**	**2.56**
75	2.14	2.10	2.13	2.12				
90	2.34		2.18					
97.5	2.56							
Max	2.63	2.20	2.47	2.29	2.38	2.15	2.07	2.63

b)

Dry Density	All	GLLD	TILLI
Samples	35	14	8
Min	1.31	1.45	1.56
10	1.48		
25	1.56	1.51	
50	**1.65**	**1.60**	**1.72**
75	1.80	1.64	
90	1.91		
Max	2.17	1.88	2.17

c)

Plasticity Index	All	GLLD	TILLI	HEG	HEAD	GGLDI	TRD	MGR	Ntm
Samples	176	43	39	18	13	9	24	13	5
Min	1	3	11	3	5	7	1	2	5
2.5	3								
10	8	9	12						
25	12	20	15	9	11		12	8	
50	**19**	**27**	**20**	**15**	**13**	**17**	**21**	**13**	**12**
75	27	35	25	30	15		25	15	
90	35	37	31						
97.5	39								
Max	53	53	38	38	24	32	40	46	22

d)

Liquid Limit	All	GLLD	TILLI	HEG	HEAD	GGLDI	TRD	MGR	Ntm
Samples	190	43	44	20	16	12	25	13	5
Min	18	19	19	18	25	22	24	22	23
2.5	22								
10	26	29	28				32		
25	31	38	31	30	29	31	37	30	
50	**39**	**52**	**40**	**35**	**32**	**38**	**45**	**34**	**26**
75	52	59	45	48	39	56	56	38	
90	61	66	52				76		
97.5	73								
Max	96	77	65	63	59	60	96	88	42

Key

- GLLD Glaciolacustrine Deposits (Lake Teifi)
- TILLI Till (Irish Sea)
- HEG Head Gravel
- HEAD Head
- GGDI Glacial and Glaciolacustrine Deposits, undifferentiated (Irish Sea)
- OAL Older Alluvium
- ALV Alluvium
- GFDUI Glaciofluvial Deposits, undifferentiated (Irish Sea)
- GFICW Glaciofluvial Deposits, ice contact (Welsh)
- GFSDW Glaciofluvial Deposits, sheet, (Welsh)
- GFDUW Glaciofluvial Deposits, undifferentiated (Welsh)
- MGR Made Ground
- Ntm Nantmel Mudstones
- Moy Moylgrove Group

Figure 38 a–d Statistical data

a) bulk density
b) dry density
c) plasticity index
d) liquid limit

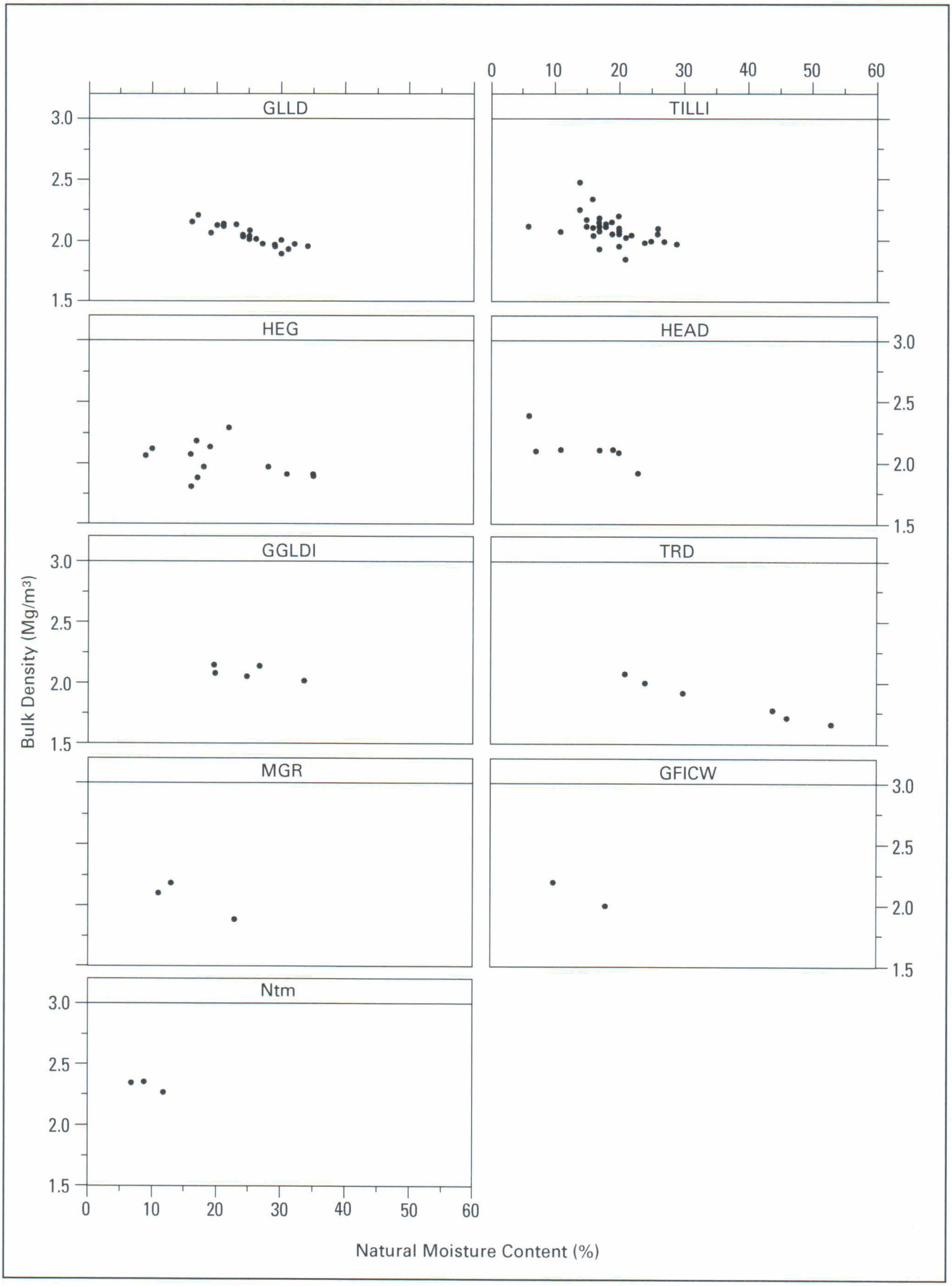


Figure 37 Bulk density/moisture content plots, key as for Figure 34.

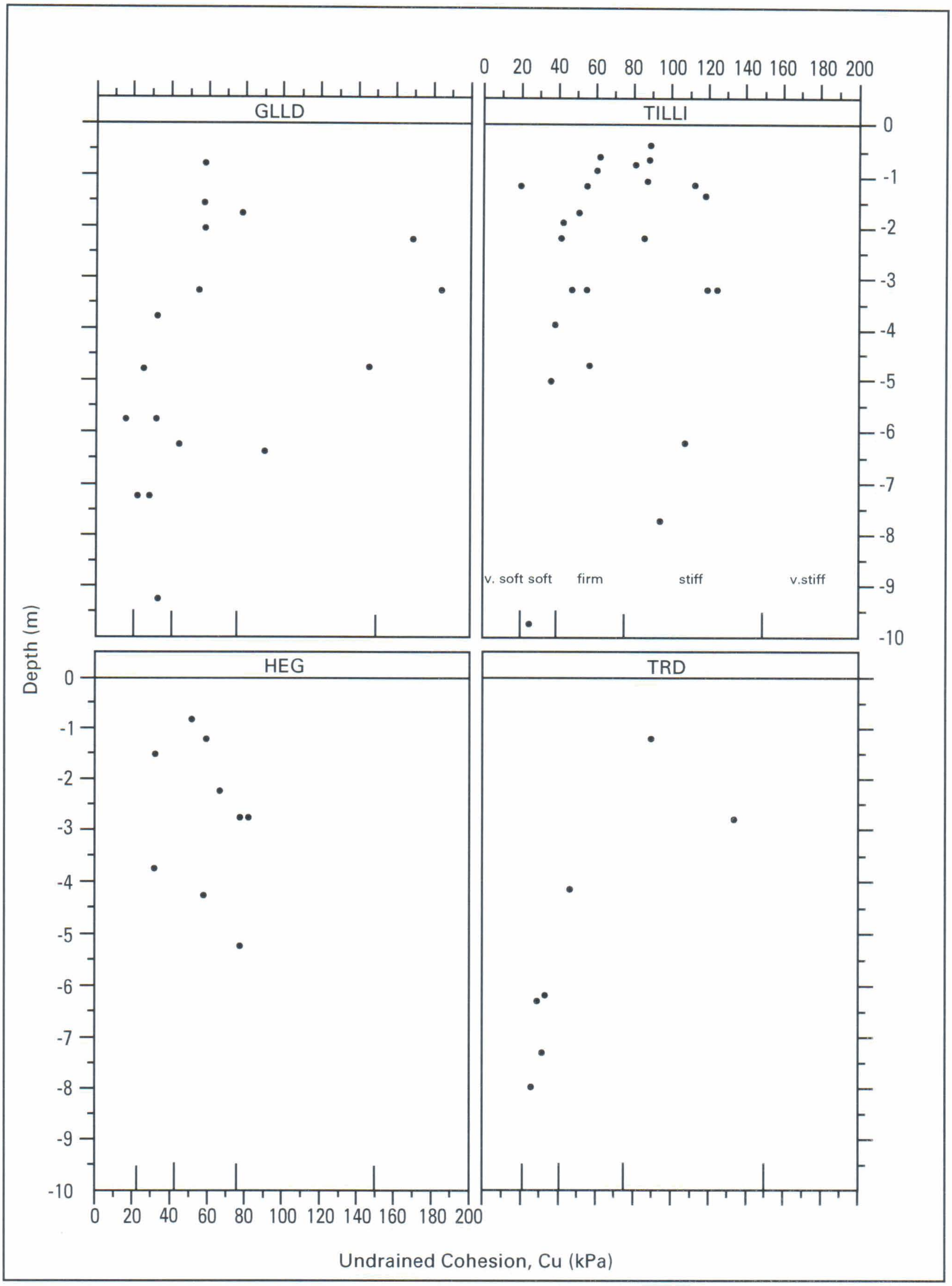


Figure 36 Undrained strength versus depth plots, key as for Figure 34.

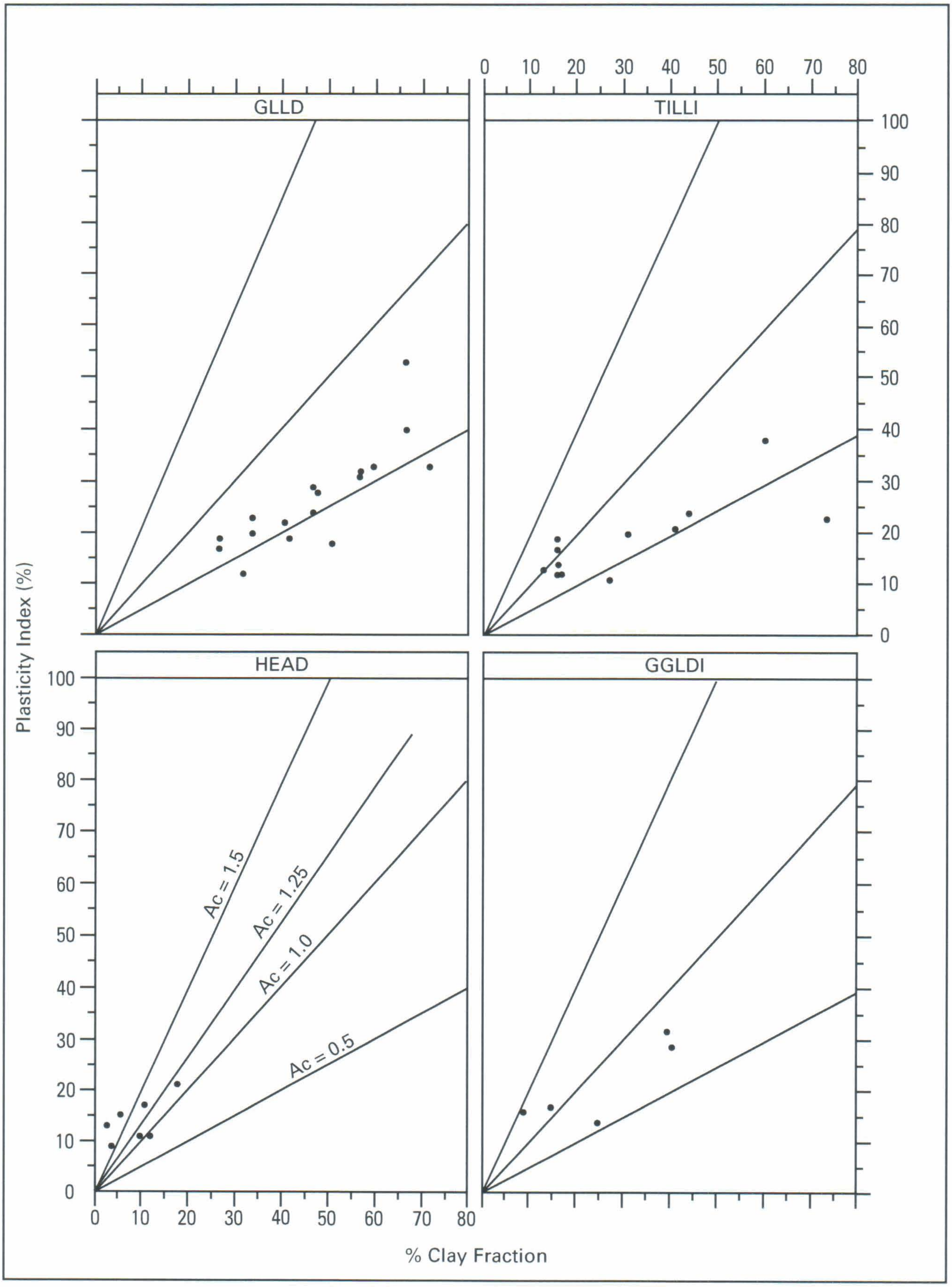


Figure 35 Activity plots, key as for Figure 34.

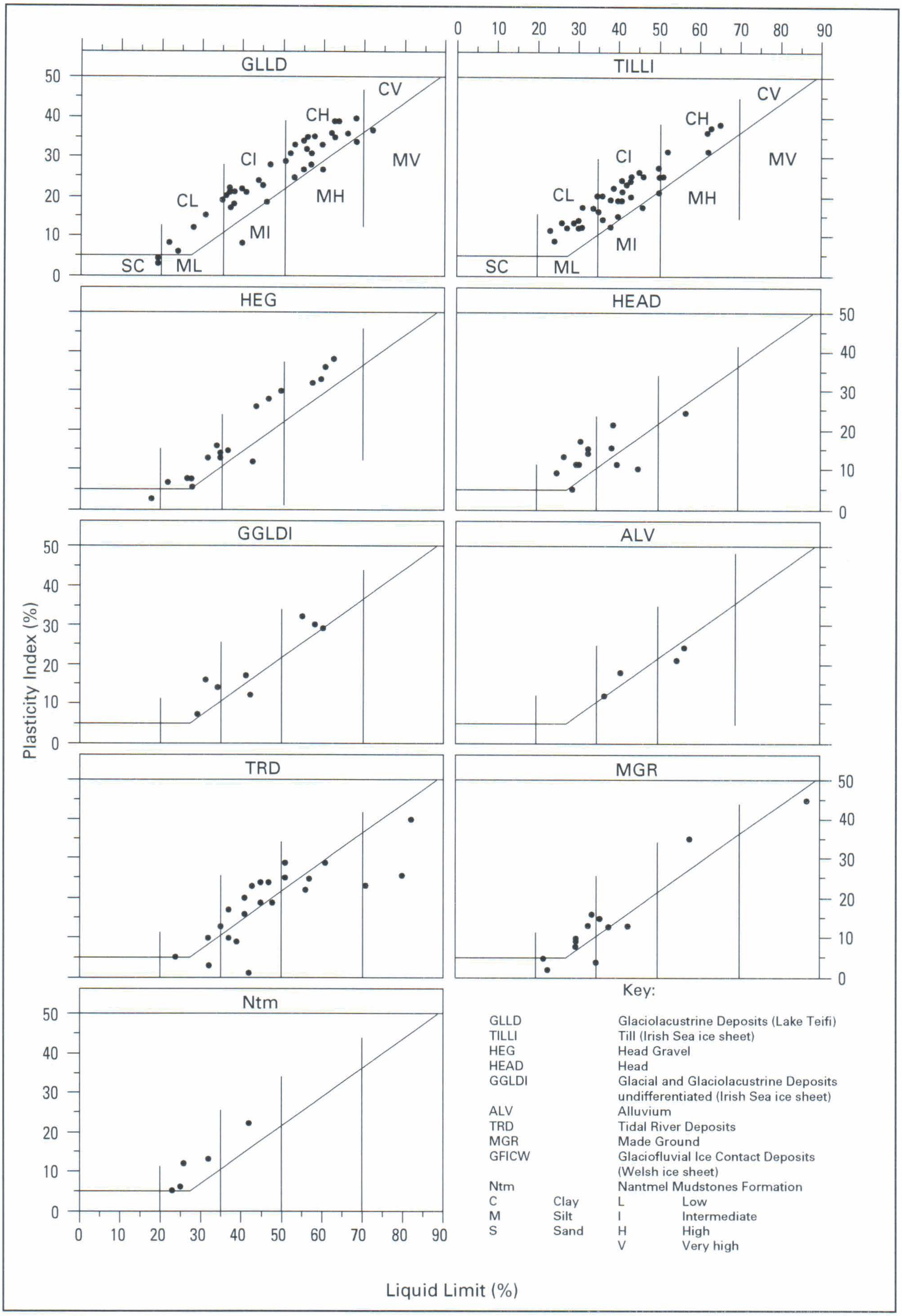
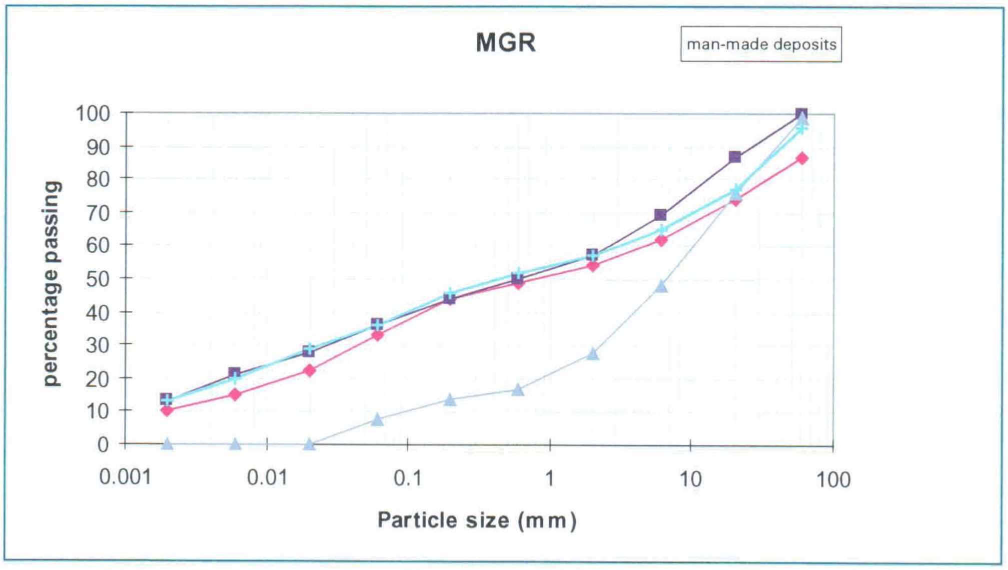
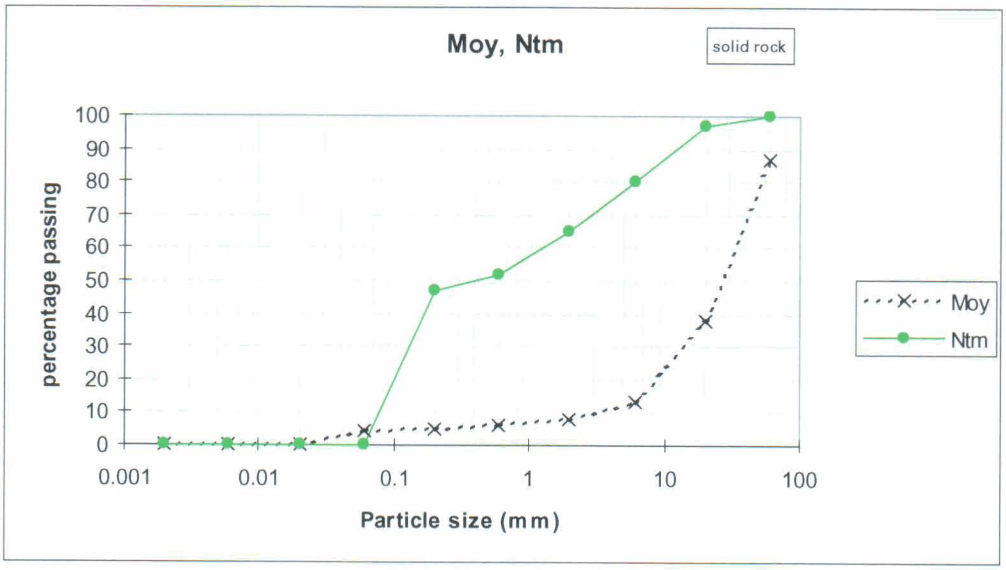


Figure 34 Casagrande plasticity plots.

Figure 33 Particle size grading plots for made ground (MGR), Moylgrove Group (Moy) and Nantmel Mudstones (Ntm).





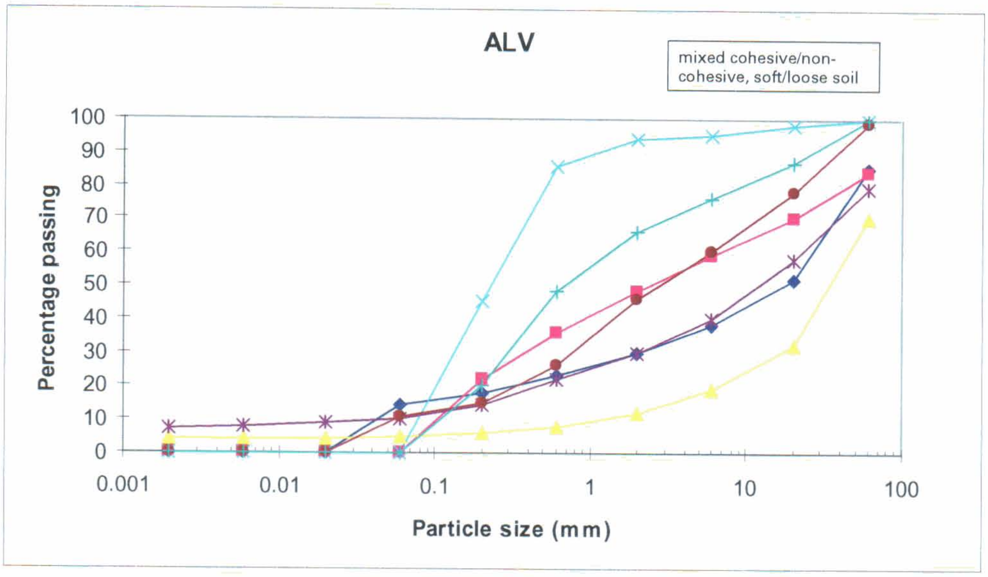
deposits where near-surface desiccation and development of hardpan contribute to strength. The glaciolacustrine deposits (Lake Teifi) appear to have a secondary strength population giving much higher values in the 'very stiff' range. The main population of the glaciolacustrine deposits (Lake Teifi) falls within the 'soft' to 'firm' groups, while the till (Irish Sea) lies mainly in the 'firm' to 'stiff' groups. The head gravel lies mainly in the 'firm' group. Insufficient data exist for the other formations with which to draw conclusions. Neither the head gravel nor the till (Irish Sea) show overall trends of strength change with depth. However, this may be accounted for by data scatter, and such trends may exist in individual profiles.

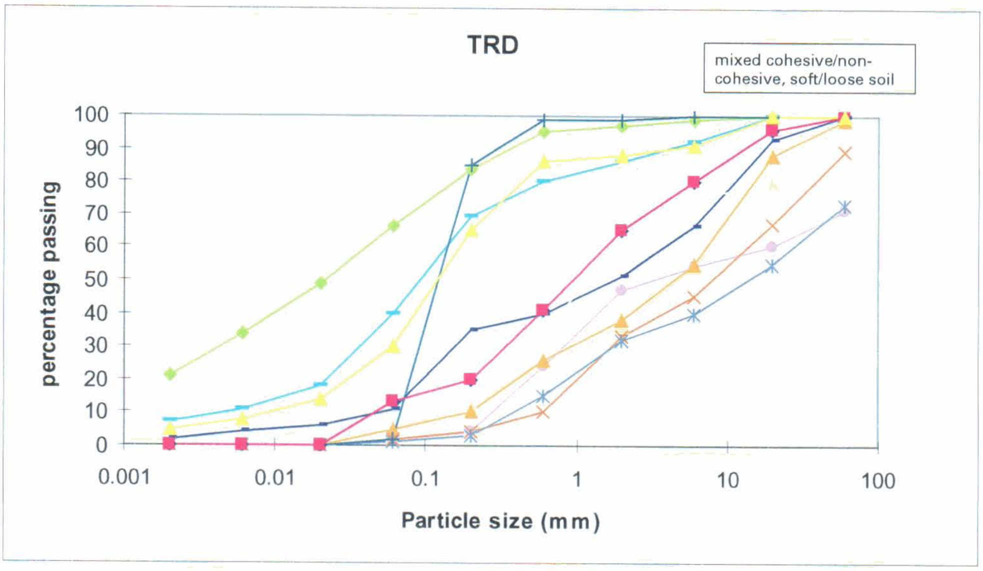
Plots of bulk density versus natural moisture content are given in Figure 37.

Statistical data for the geological units in the geotechnical database are shown in Figure 38. It includes minima, maxima, and a range of percentiles from 0.5 to 99.5; the 50th percentile being the *median* value (i.e. the value above and below which 50% of data lie).

Summary statistics for standard penetration tests (SPT) show that N values for the materials tested range from 5 to in excess of 300 (values shown as '300' indicate that the N value *exceeds* 300. In terms of *median* values glaciolacustrine deposits (Lake Teifi), glaciofluvial sheet deposits (Welsh), and made ground may be classed as 'soft' to 'firm', head gravel as 'stiff', alluvium, glaciofluvial deposits, undifferentiated (Irish Sea) and glacial and glaciolacustrine deposits, undifferentiated (Irish Sea) as 'very stiff', while the remaining groups are 'hard' (Clayton, 1995). It should be noted however that, with the exceptions of glaciofluvial ice-contact deposits (Welsh), glaciofluvial deposits, undifferentiated (Welsh), older alluvium, and Molygrove Group, all groups' *minima* are below N'15 (i.e. they in the 'soft' to 'stiff' range). Ratios of median undrained cohesion, Cu to median SPT, range from 2.5 to 5.5. These are slightly lower than values quoted by Stroud and Butler (1976) for comparable soils. **These data should be treated with caution as a large part of the data set was obtained from the St Dogmaels Landslide, and may therefore give lower values than the equivalent undisturbed material.**

Figure 32 Particle size grading plots for alluvium (ALV), tidal river deposits (TRD) and glaciofluvial deposits, undifferentiated, (Irish Sea) (GFDUI).





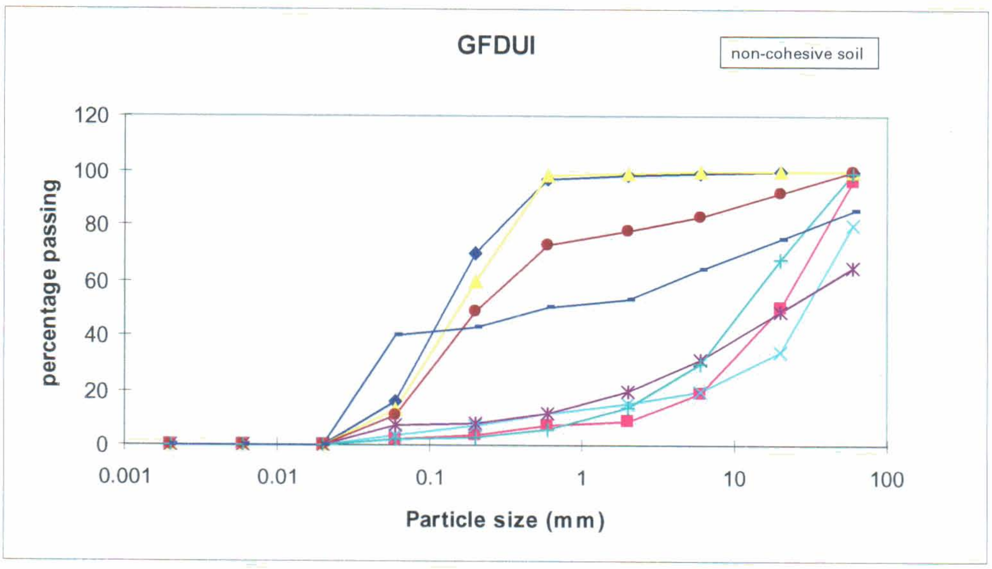
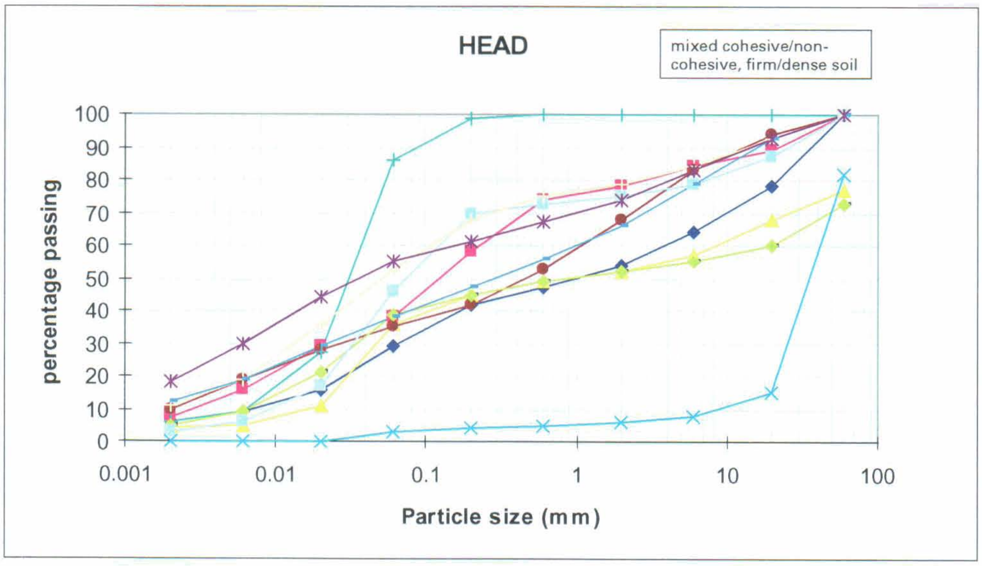
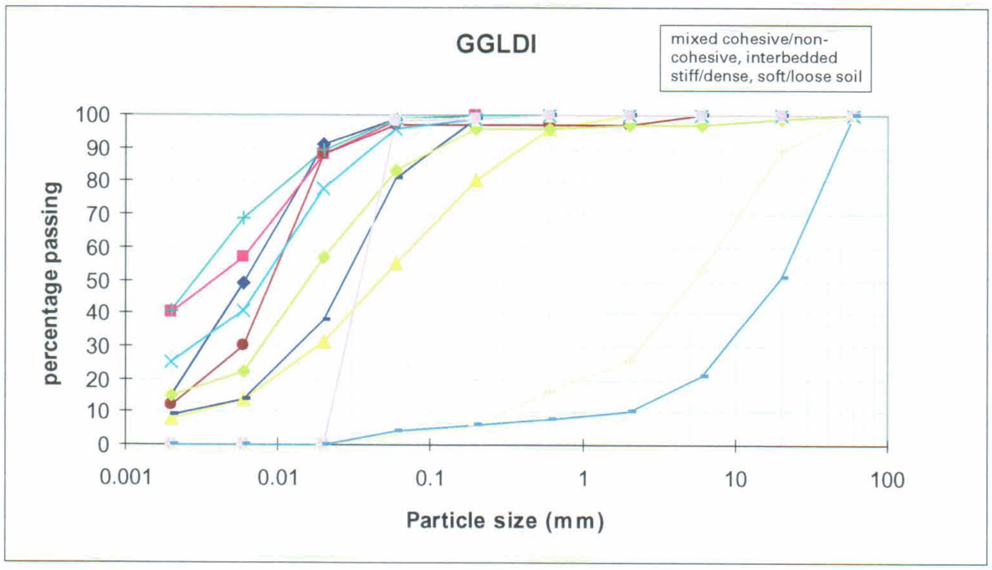


Figure 31 Particle size grading plots for head (HEAD), glacial and glaciolacustrine deposits, undifferentiated (Irish Sea) (GGLDI) and older alluvium (OAL).





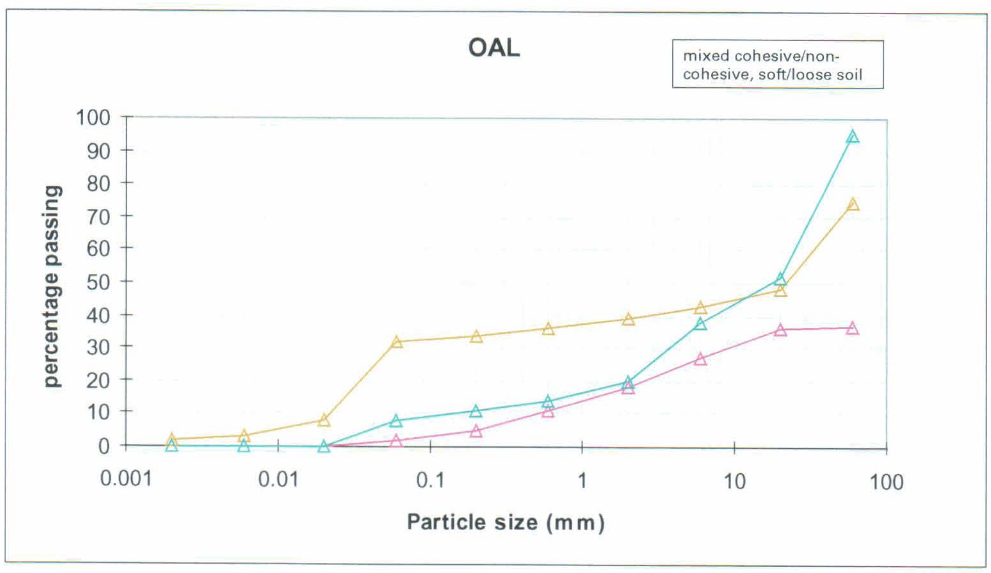
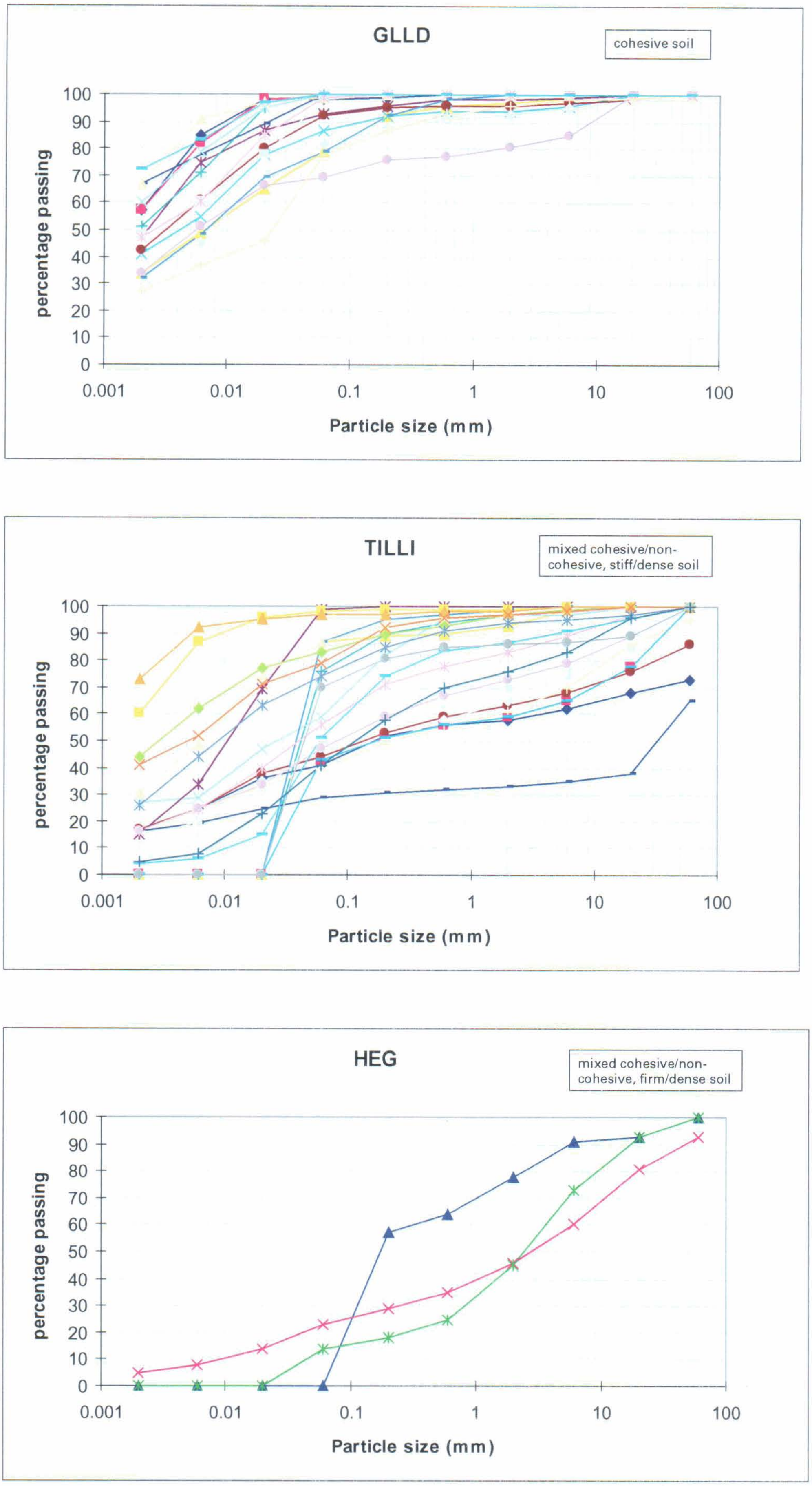


Figure 30 Particle size grading plots for glaciolacustrine deposits (Lake Teifi) (GLLD), Irish Sea till (TILLI) and head gravel (HEG).



Appendix 4 — Geotechnical properties of materials

INTRODUCTION

For the purposes of producing a geotechnical assessment of the major superficial (drift) deposits in the area, a geotechnical database was set up using data obtained from 25 of the site investigation reports, collected during the survey (see Appendix 1) (Hobbs et al., 1997). The remaining 15 reports either contained unsuitable data or none at all. This database was formed on Microsoft Access V.2™ using the Association of Geotechnical and Geoenvironmental Specialists format where possible. The database is based on 158 boreholes and 520 samples and consists of results from a range of geotechnical laboratory tests including particle size analysis, Atterberg limits, undrained strength, density and moisture content, and also standard penetration tests. These parameters have been analysed for this report and presented in a way that enables trends for different superficial formations to be compared. In some cases few data are available and the scope for conclusions about likely geotechnical properties or engineering behaviour can only be limited. There was no data available from site investigation reports for the following superficial deposits: Welsh till, heterogeneous glacial deposits, glaciolacustrine deposits (Welsh), alluvial fan deposits, river terrace deposits, shoreface and beach deposits, blown sand, peat, lacustrine deposits, saltmarsh deposits, landscaped ground and disturbed ground. The solid formations consist mainly of mudstones with subordinate sandstones. The mudstones show weathering, folding and a strong cleavage. The solid formations are not well represented in the geotechnical database; only the Moylgrove Group and Nantmel Mudstones Formation are represented.

Graphical presentations have been made in Microsoft Excel V.6™ and Mathsoft Axum V.5™. The geotechnical data are given in graphical form in figures and as a statistical breakdown.

Geotechnical properties of materials in the database

The database includes the following geological units:

Superficial deposits
Made ground
Alluvium
Older alluvium
Tidal river deposits
Head
Head gravel
Glaciolacustrine deposits (Lake Teifi)
Glacial and glaciolacustrine deposits, undifferentiated (Irish Sea)
Glaciofluvial deposits, undifferentiated (Irish Sea)
Glaciofluvial deposits, undifferentiated (Welsh)
Glaciofluvial ice-contact deposits (Welsh)
Glaciofluvial sheet deposits (Welsh)
Till (Irish Sea ice sheet)

Solid
Moylgrove Group
Nantmel Mudstones Formation

The particle-size grading plots (Figures 30 to 33) show clear groupings of data where there is sufficient data. Individual anomalies are ignored for classification purposes. Elsewhere, the trends are difficult to define and individual anomalies cannot be identified. There is a reasonably clear distinction in grading terms between glaciolacustrine deposits (Lake Teifi) and glacial and glaciolacustrine deposits, undifferentiated (Irish Sea); the latter being generally coarser than the former. The clay fraction for glaciolacustrine deposits (Lake Teifi) ranges from 27 to 72%, while for glacial and glaciolacustrine deposits, undifferentiated (Irish Sea) it is 7 to 40%. Head is notable for its well-graded (poorly-sorted) characteristic, as is the majority of the till (Irish Sea). However, there appears to be a small secondary population within till (Irish Sea) from which all particles smaller than coarse silt are absent. The wide spread of till (Irish Sea) data from clay and silt, to silty sand and gravel is also notable. A small secondary population of finer grading is seen for tidal river deposits.

The Casagrande plasticity plots show similar groupings for glaciolacustrine deposits (Lake Teifi), till (Irish Sea) and head gravel (Figure 34). However, the glaciolacustrine deposits (Lake Teifi) data are more concentrated at the 'high plasticity' end than the till (Irish Sea). The head gravel data are too few to make a clear comparison, but appear to be concentrated at the 'low' end. The tidal river deposits data shows considerable scatter with many data points falling below the A-line. This suggests the influence of silty or organic material. Perhaps surprisingly, head shows only 'low' and 'intermediate' groups. The data for made ground are probably not sufficient in number to be statistically significant for such a heterogeneous material. The Casagrande plot for the Nantmel Mudstones Formation has probably been carried out on weathered near-surface bedrock material.

The Casagrande plasticity plot should not be used as an indication of particle size grading. There may appear to be discrepancies between the particle size grading plots and the Casagrande plasticity plots for some materials. An example of this is head gravel which has an essentially non-cohesive particle size grading but at the same time a 'low' to 'high plasticity' rating on the 'clay' side of the A-line. This is not actually a discrepancy, because the tests carried out to determine plasticity, sieve out all sizes larger than silt. The plasticity data therefore shows that the fine fraction of the soil has a 'low' to 'high plasticity' rating. In the case of the head, results indicate a dominantly coarse soil with plastic fines. This is reflected to some extent in the 'activity' parameter (Figure 35), which is defined as the ratio of plasticity index to clay size fraction (%). Head gravel shows the highest values for activity (> 1.25) in the 'active' range. This parameter is largely a function of clay mineralogy, but may also be affected by reworking.

Strength data are shown for selected formations in Figure 36. The tidal river deposits and to a lesser extent the glaciolacustrine deposits (Lake Teifi) show a trend of decreasing strength with depth. This is normal for such

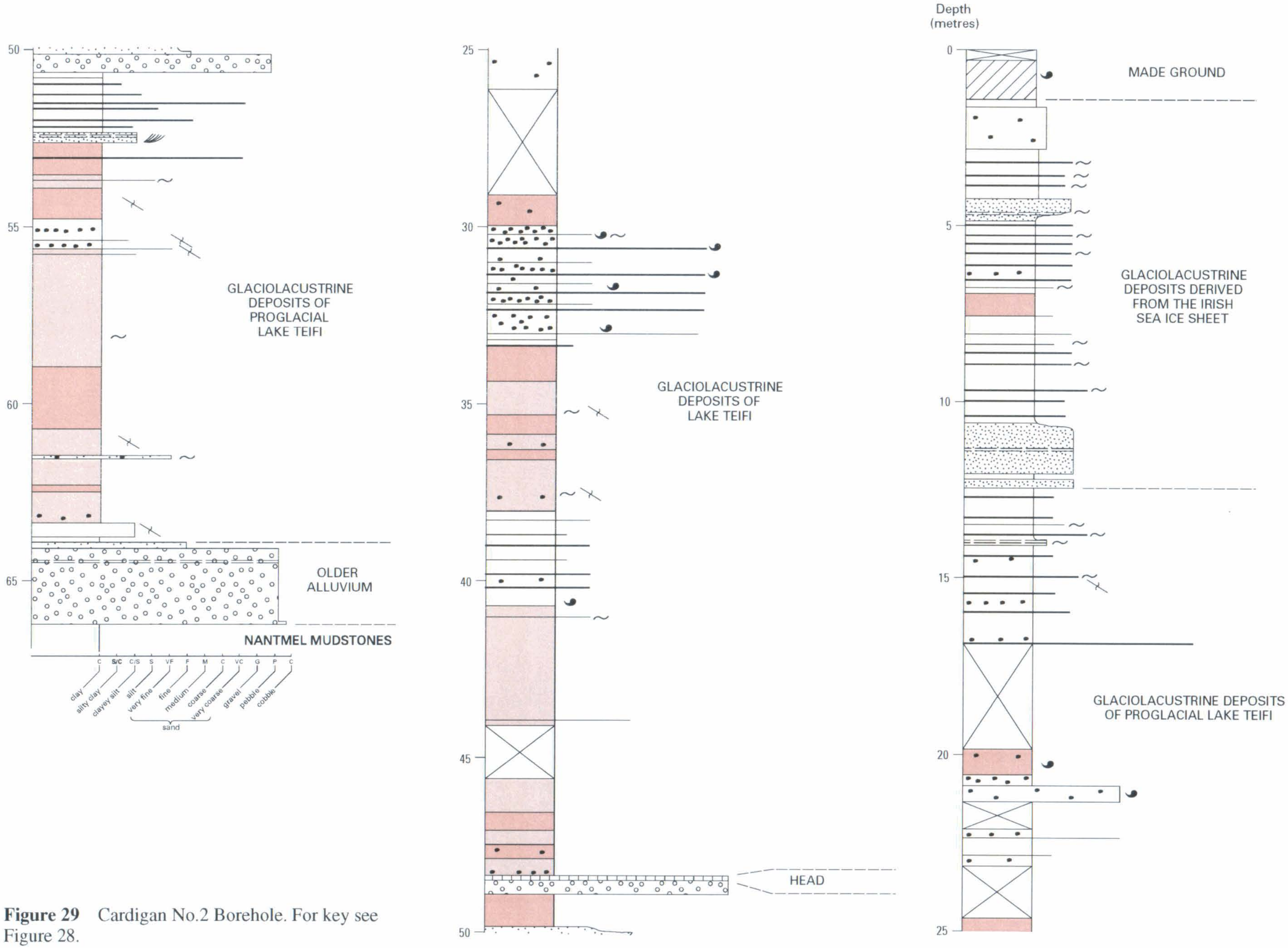


Figure 29 Cardigan No.2 Borehole. For key see Figure 28.

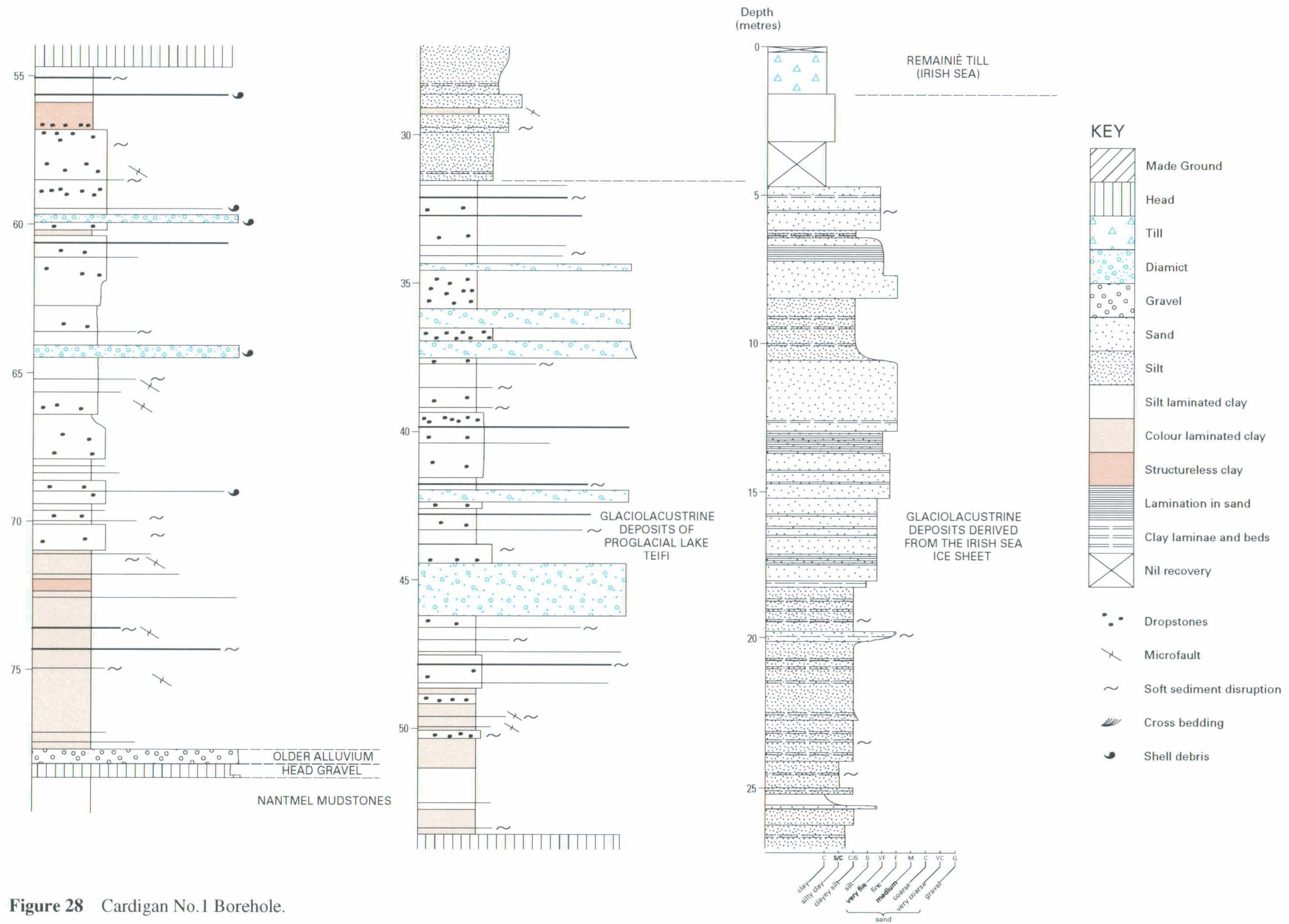


Figure 28 Cardigan No.1 Borehole.

Appendix 3 — Drilling programme

As naturally occuring, thick, vertical sections are generally absent in drift deposits, drilling is the best technique for establishing the sucession of deposits and, thereby, their geological history. The only drawback is cost, good quality drilling being expensive.

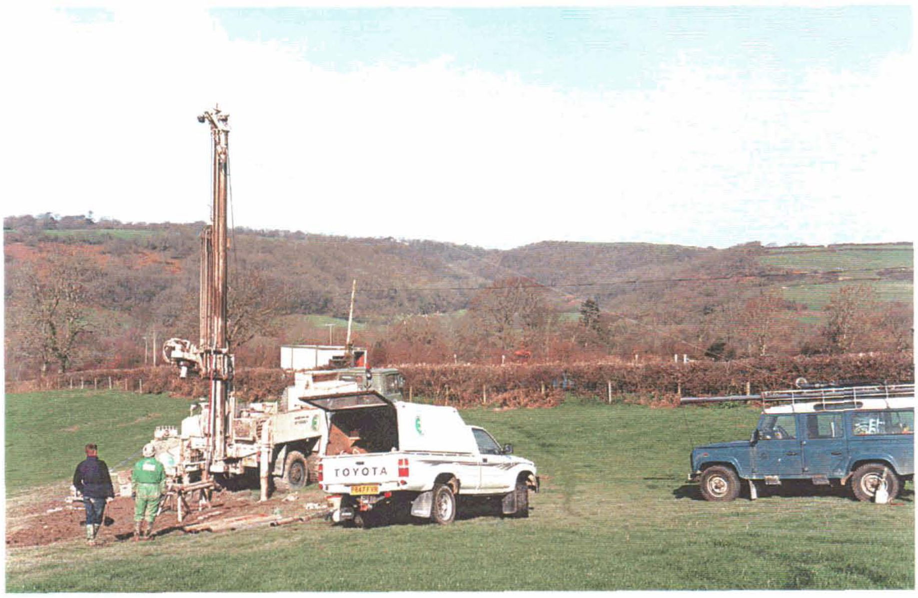
It was considered likely that the thickest sequences of drift deposits were preserved in the abandonded courses of the Afon Teifi; therefore, a drilling programme was established to investigate two of them. It was decided to use rotary coring rather than percussion, as core provides a continuous undisturbed sample. The sites were chosen following geophysical surveys (Appendix 2), which established the position of the deepest parts of the buried valleys. Cardigan No.1 Borehole [1768 4764] (Figure 28), at c. 40 m O.D., was sited at Llwynpiod Farm, just north of Cardigan. Cardigan No.2 Borehole [1761 4285] (Figure 29) (Plates 25 and 26), at c. 41 m O.D, was situated at Pen-y-bryn, south of Cardigan.

The boreholes were drilled in March 1997 by Exploration Associates Ltd and supervised by BGS geologists. A lorry-mounted, top-drive rig was used. Due to the nature of the drift deposits, both conventional and wireline (Geobore 'S') techniques were employed using a bio-degradable polymer as a drilling mud. The core was retained in 100 mm diameter clear plastic coreliner. Core recovery was generally good in the clays, but poor in the silts and sands. The cores were sealed on site and taken to BGS Keyworth for logging. Once the coreliner had been cut, the cores of drift deposits were cut in half lengthwise with a cheese wire. Once logged each core was stored in layflat plastic sleeving to preserve the moisture content. The cores are curated in the BGS NGRC corestore.

Following the completion of the drilling, each borehole was geophysically logged using a digital gamma ray logging tool.

Plate 26 Structureless and laminated glaciolacustrine clays (Lake Teifi) with an interbedded unit of sand and gravel, Cardigan No.2 Borehole, depth 47.9–52.5 m [1765 4280].

Plate 25 Drilling Cardigan No.2 borehole [1765 4280], Pen-y-bryn.



found here can be differentiated from the Nantmel Mudstones Formation which occurs further west. The resistivity of the deepest unit detected is not well defined and may be less than 1500 ohm.m.

Traverse GT6

This short traverse, 3 km west of Llanybyther (Figure 16), shows evidence of up to 15 m of glacial deposits associated with the Nant Cledlyn and some thickening of superficial deposits on the higher ground to the west (Figure 27), although the residual gravity anomaly amplitude is only 0.3 mGal. The deepest part of the buried valley now lies at 80 m above OD. Mapping suggests that the deposits comprise glacial sand and gravel with, perhaps, some till.

The resistivity data from RS1 and RS2 are consistent with the results from GT5 in showing no evidence of glaciolacustrine clays. Bedrock resistivities are clearly less than 1000 ohm.m to depths of over 100 m, confirming a systematic change in lithology rather than effects linked to enhanced weathering or fracture content.

CONCLUSIONS

The combination of gravity traversing and resistivity sounding data proved successful both in indicating the general form of buried buried valleys within the valley of the Afon Teifi and in providing some evidence of the nature of the buried valley deposits themselves.

Gravity profiles alone would have been adequate for defining the deeper parts of the buried valleys in a qualitative sense but without being able to differentiate glaciolacustrine clays from coarser deposits.

Resistivity data were subject to more uncertainty as a result of distortions in the sounding curve and the limited applicability of the assumption of a one-dimensional model (ie. with uniform horizontal layering). However, they effectively identified the presence of conductive glaciolacustrine clays and suggested where thicker silts and gravels occur; identification of tills as such was not possible except by inference with respect to the bedrock profile indicated by the gravity models. Resistivity data also picked up a change in the character of the underlying Ordovician bedrock, with less resistive units coming in to the east between traverses GT3 and GT5.

By making gravity and resistivity models compatible both with each other and with the results of previous seismic surveys, the range of equivalent solutions was reduced significantly. Preliminary interpretations gave depths to bedrock accurate to within about ten percent as established subsequently by drilling at Cardigan No.1 and 2 boreholes; the basic characteristics of the sequence were also indicated correctly as being somewhat at variance with the initial geological model.

Traverse GT3

This north-south orientated traverse was sited north of Cenarth (Figure 16). Prior to drilling, the best available control for the modelling, was provided by depths to bedrock interpreted from the seismic refraction line near Cenarth (Francis, 1964), close to traverse GT3. This put the deepest part of the buried valley at 9 m below OD, with a drift thickness of 69.5 m.

The gravity profile shows a broad anomaly low with a minimum at GT3/710 m (Figure 23). Regional gravity anomaly values increase to the north by about 0.5 mGal/km and a slightly steeper gradient was assumed on the basis of the profile data, with an increase of 0.6 mGal over its 1100 m length. The actual background level is particularly difficult to establish here as the traverse did not extend far enough on to a known area of shallow bedrock. However, some control is provided by the local gravity anomaly high at GT3/200 m in combination with the 2D modelling, by assuming the feature is not associated with a local increase in bedrock density. Thus, with the bedrock almost at outcrop here, the residual anomaly still needs to be as much as 0.5 mGal.

Resistivity soundings RS1 to 2 strongly suggest a sequence similar to that found in Cardigan No.1 Borehole, with clayey silts overlying lacustrine clays. RS1 is distorted by poor quality data where the potential dipole length was increased, possibly indicating near-surface variations, but at neither site is there any good evidence of thick, basal river gravels. RS3 probably lies beyond on the northern margin of the main buried valley, with the silts and clays being replaced by head. Bedrock resistivities still appear to be consistently above 1000 ohm.m on this line.

The interpreted form of the buried valley is consistent with the seismic results, showing a relatively flat base at about 10 m below OD, which continues south of the bedrock high at GT3/200 m. As before, the model is intended mainly as a qualitative guide and the interface within the buried valley deposits is only a representation of lateral variations. However, it seems probable that the interface detected at depths of 15–20 m in the seismic reflection survey south of Llechryd (Nunn and Boztas, 1976), between GT2 and GT3, represents the base of the clayey silts, rather a boundary between lacustrine clays and till as suggested; this would also be more consistent with the inferred layer velocities.

Traverse GT4a

This gravity only traverse crossed the Afon Teifi at Newcastle Emlyn (Figure 16). The residual anomaly amplitude is now about 1 mGal, on the assumption that the background field has a smooth form controlled by shallow bedrock at both ends of the line. Existing boreholes located about 200 m to the south-east of the traverse encountered bedrock beneath 18–20 m of glaciolacustrine clays, possibly laminated and with interdigitated head at some sites. Projecting the rockhead values in these boreholes onto the traverse, gives their locations in the zone GT4a/350–400 m, near the edge of the buried valley.

The model (Figure 24) assumes that the deepest bedrock lies close to OD, i.e. somewhat higher than at the downstream site of GT3. This implies that the density of the buried valley deposits is less than that of the glaciolacustrine clays found further to the west; this, in turn, suggests that silts rather than clays predominate. Possible explanations for the relatively low 'clay' density inferred for the buried valley deposits are:

- Lateral variations in the buried valley deposits away from the boreholes, possibly including gravels preserved near the base.
- The bedrock underlying the buried valley, GT4a/350–700 m, has a lower density than elsewhere, thus accounting for some of the gravity anomaly; this could represent a fractured/weathered zone or a more arenaceous rock type.

The presence of lower density near-surface material around GT4a/400 m is indicated by the steep anomaly curvatures here; it could represent the gravels which are seen locally within about 100 m to the north-west of the traverse.

The anomalous gravity values recorded at GT4a/850–900 m are linked to stations on or near the bridge crossing the Afon Teifi. Bedrock is seen at outcrop beside the traverse to the north of the river and the drift sequence included in the model to account for the variations in gravity anomaly can be taken as an indication of the weathered rock profile rather than a continuation of the Quaternary deposits. Similarly, at the south-western end of the line, the thin cover probably comprises a mixture of head and weathered bedrock.

Traverse GT4

The amplitude of the residual gravity anomaly on this 2.25 km long traverse south of Afon Teifi between Llangeler and Llandysul (Figure 16) is now less than 0.6 mGal and shows no evidence of a significant buried valley (Figure 25). There is some difficulty in establishing the background field level but it appears that bedrock is effectively at outcrop at GT4/1100 m and remains at shallow depth over most of the eastern half of the line until the evidence of thicker drift beyond GT4/2200 m. A maximum thickness of 30 m for the superficial deposits is implied in the model, given the relatively high density of 2.25 Mg/m^3 used.

Traverse GT5

This traverse was situated south-east of Llandysul (Figure 16). Resistivity soundings RS1 to 3 show a markedly different character from that seen further to the west. In particular, there is no evidence of the low resistivities associated with the glaciolacustrine clays and it is difficult to differentiate any buried valley deposits from the bedrock response. Glaciolacustrine clays are known to be present in this buried valley, although they may be in the form of lenticular deposits. The bedrock resistivity itself also appears to vary, with lower interpreted values (500–1000 ohm.m) than seen previously.

There is good evidence of a buried valley near the centre of the line from the gravity anomaly profile (Figure 26), where the residual anomaly amplitude is nearly 1 mGal. RS2, in the centre of this zone, is somewhat distorted but the resistivity of the bulk of the buried valley deposits is in the range 150–200 ohm.m; this could represent till and/or gravel. The assumed density value of 2.05 Mg/m^3 is intermediate between the two and it is likely that both are in fact present, in the form of a gravelly till.

The gravity model confirms that the intermediate resistivity values interpreted from RS1 and RS3 do represent bedrock, implying that the Yr Allt Formation significant thickness of river gravels filling the bottom of the buried valley. It should be noted, however, that apparent resistivities of <15 ohm.m could be associated with sand and gravel if they contain brackish saline water. Values of 1500 ohm.m assigned to the bedrock are not proved by the data as the arrays were not expanded far enough to get beyond the steeply rising section of the sounding curve: the adopted values are close to the minimum which allows the curves to be matched, without implying any upper limit.

The preferred starting model assumed a density boundary located, arbitrarily, near OD within the valley deposits. In this case, a higher density was adopted for the deeper buried valley fill on the basis of the resistivity data which implied that clay rather than gravel was the main constituent here. By subdividing the buried valley deposits in the gravity model in accordance with the resistivity interpretation, it is possible to match the anomaly curvatures more closely than with the homogeneous fill, as a shallower interface is available even though the density contrasts are no greater. The provisional interpretation produced prior to drilling on this line suggested bedrock at about 25 m below OD, with a silty layer about 30 m thick overlying glaciolacustrine clays.

Cardigan No Borehole 1 was located near GT1a/300 m, based, in part, on the geophysical evidence. Preliminary logging results indicate a coarsening-upwards sequence (clayey silt, silt, fine-grained sand) to a depth of 30.5 m, followed by a clay-dominated zone with stoney bands to 77.5 m; 1.5 m of basal gravels were underlain by Ordovician mudstone to the base of the hole at 81 m depth. The glaciolacustrine clays became noticeably stiffer in the lower part of the sequence. These findings are in good qualitative agreement with the geophysical interpretations, although the depth to bedrock was somewhat underestimated. The revised gravity model (shown in Figure 20) used slightly higher density values in order to improve the correlation. An increase of density with depth in the clays was incorporated across the horizontal interface near OD. It was not possible to adjust the model of the closest resistivity sounding, RS1, to fit exactly. This discrepancy is readily accounted for by the offset of the centre of the array from the borehole site. RS2 is also rather poorly defined at depth, as a result of a large offset at the change in potential dipole length.

The form of the silty zone inferred in the gravity model is highly speculative in that the gravity anomaly has been split arbitrarily into more than one layer and the density values may, in practice, be more variable laterally within the same geological unit. As noted above, the main justification for the uppermost silty layer is in providing the means to account for the sharper anomaly curvatures seen in the observed data. Similarly, the interpreted bedrock surface can be varied in detail, although the overall qualitative form illustrated should hold. For example, there is evidence of terraces and/or buried valleys flanking the axis of the valley.

Traverse GT1

This gravity traverse was sited through the centre of Cardigan (Figure 16) in order to delineate the buried valley in an area where thick tills and glaciolacustrine clays blanket both the valley and adjacent interfluves. The background field was set almost horizontal as the regional data gave no clear indication of the form of the background gradient. Anomaly values were still rising at both ends of the traverse, indicating that the superficial cover was continuing to thin away from the main buried valley.

The local gravity anomaly has a maximum amplitude of about 1.5 mGal, with a broad low extending over a width of 800 m being subdivided by a secondary, central high (Figure 21). In fact, when plotted in relation to the topography, the lower anomaly values to the north-east have the effect of maintaining the base of the buried valley close to its 'average' level of about 20 m below OD. This level could be raised closer to OD by extending the cover of lower density silts in the model, which would be more consistent with the interpretation shown for GT1a; alternatively, the model for GT1a may exaggerate the contribution from silts. The 'over-deepened' buried valley seen near GT1/800 m can be correlated directly with the main feature on GT1a. The use of slightly lower densities for the clays on this line is not considered significant, given that they can be offset by slight changes to the level of the background gravity field.

Traverse GT2

This east-west oriented line near Cilgerran (Figures 16 and 22) was particularly instructive in illustrating the benefits of geophysical surveys in this type of environment in that it indicated a marked asymmetry in the bedrock profile beneath the mapped buried valley. Resistivity sounding RS4 suggested that the nature of the buried valley fill deposits differed from line GT1a in that the clay content appears to reduce rather than increase with depth; that is, some increase in intermediate resistivity values with depth was observed. Low resistivity values, of less than 15 ohm.m interpreted for the superficial deposits at the other soundings, RS1 to 3 indicated that clays predominated. The gravity model was constructed on this basis, with lower density material (silts–gravel) filling the deeper part of the buried valley, overlain by a cover of lacustrine clays.

The gravity anomaly profile clearly restricts the main buried valley to the western end of the line, with the possibility of a subsidiary buried valley to the east. As the resistivity soundings were all offset by at least 150 m from the traverse line, some difference between the resistivity and gravity models is to be expected. However, the limited amplitude of the residual gravity anomaly relative to the resistivity models RS1 to 3 to the east of the main buried valley, suggests that the density of the clays is higher here, as adopted in the gravity model; alternatively, the background field could be raised to the east. It should be noted that station number 79 which occurs on a short dog-leg in the traverse, was omitted in constructing the gravity profile.

Cardigan No.2 Borehole was sited near GT2/460 m. Clayey silt was found to a depth of 14 m, underlain by glaciolacustrine clays with occasional sand and stoney beds to 48 m (near OD); 5 m of sand and gravel were followed by 11 m of clay with a further 3 m of sand and gravel to a depth of 67 m; Ordovician bedrock, with 1 m of regolith was proved to the base of the hole at 73 m.

The increased thickness of sand and gravel at depth at this site relative to Cardigan No.1 Borehole is taken to account for the change in character of the resistivity sounding response, albeit that neither the actual thickness nor its depth of occurrence can be determined reliably. The observed thickness of gravel is unlikely to result in the bulk density of as low as 1.95 Mg/m^3 used in the gravity model; a single layer of intermediate density within the buried valley may be more realistic.

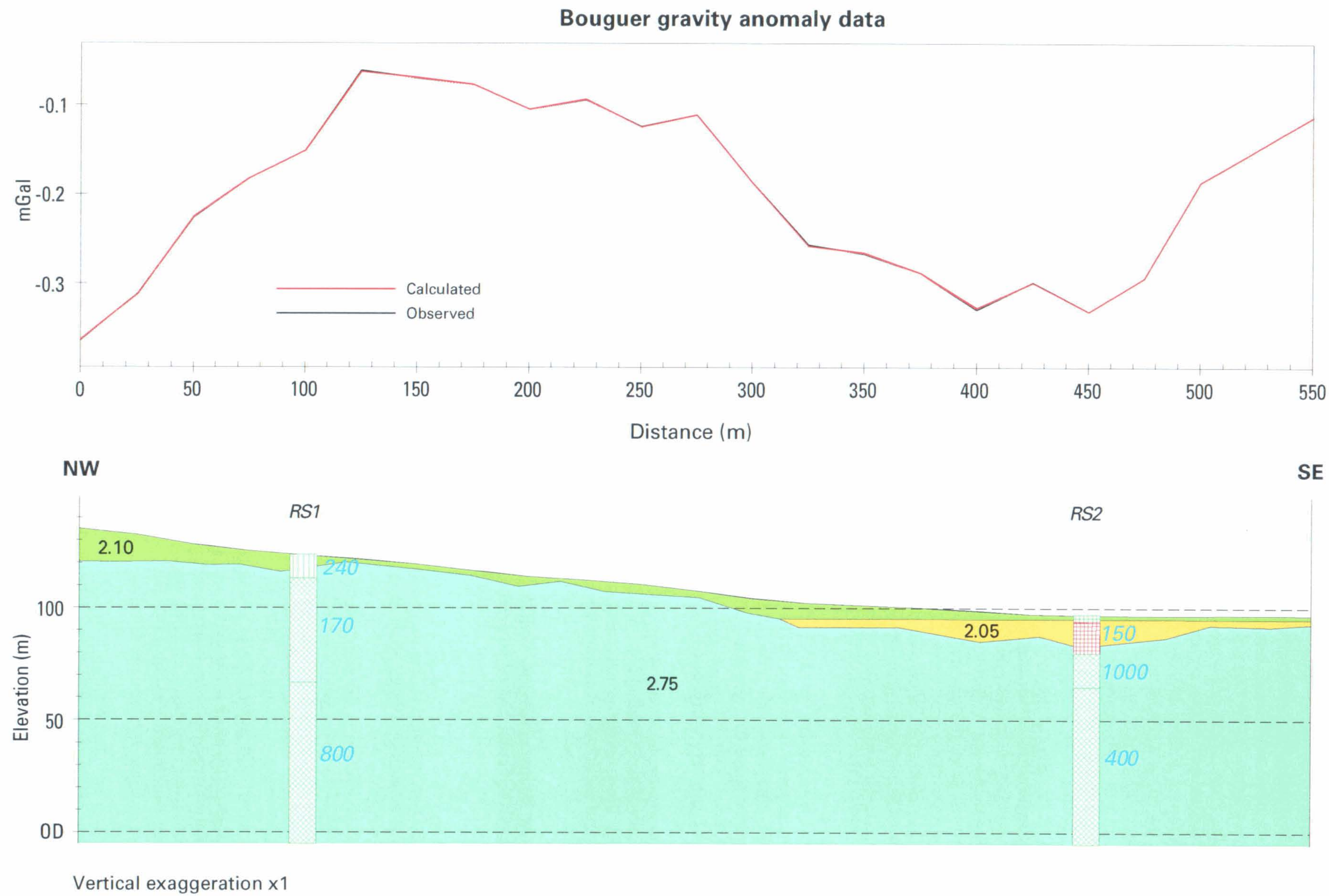


Figure 27 Gravity profile and 2D model with resistivity interpretations for traverse GT6.

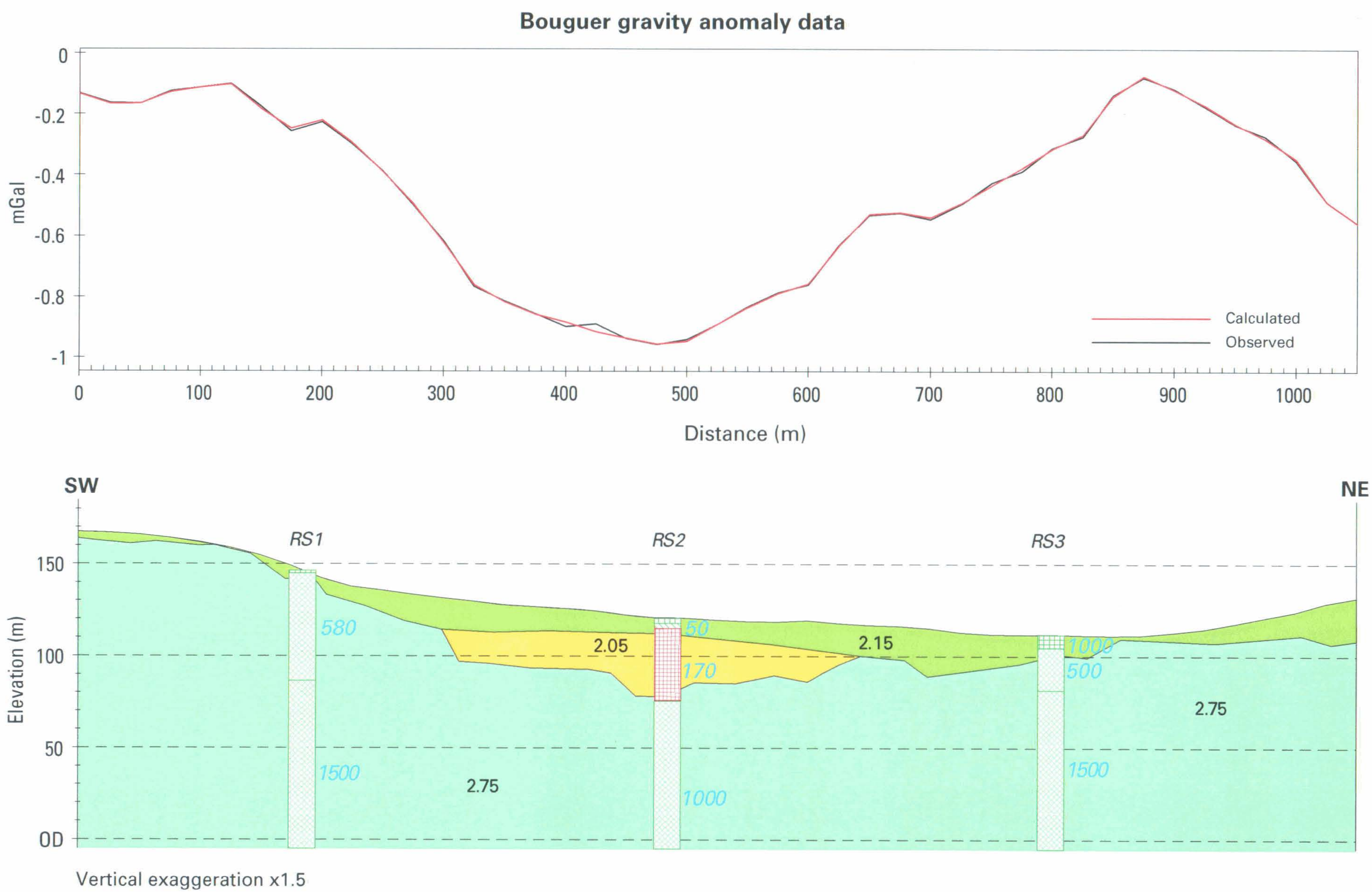


Figure 26 Gravity profile and 2D model with resistivity interpretations for traverse GT5.

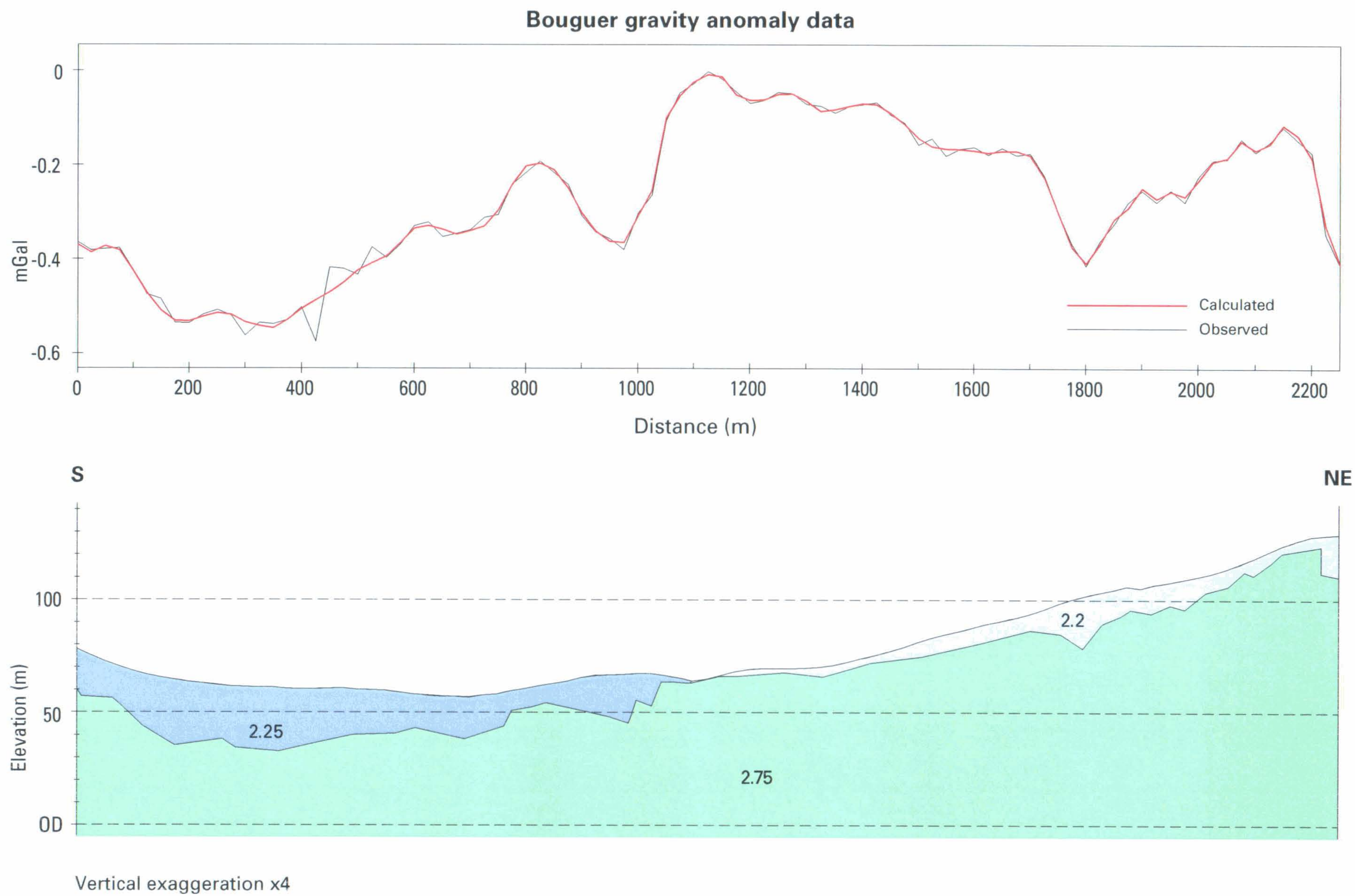


Figure 25 Gravity profile and 2D model for traverse GT4.

Glossary

Alluvium Material (*sediment*) carried by a river or stream and deposited on its floodplain

Alluvial Pertaining to the deposits of a river or stream

Alluvial fan Spread of *alluvial* material with a fan-like form; usually developed where a tributary stream enters the main valley

Aquifer A water bearing body of material (sediment or rock) which is, or which has potential as, a source of *groundwater* to wells, boreholes or springs

Artesian water *Groundwater* trapped under pressure

Artesian pressure Hydrostatic pressure of *artesian water,* which determines the height above landsurface the water rises to, when encountered in boreholes or in surface excavations

Ablation Melting of ice in situ (also wasting)

Basin A large depression in which sediments accumulate (hence sedimentary basin)

Bedding The arrangement of *sedimentary rocks* in beds or layers of varying thickness and character

Bedrock Solid rocks that occur at the surface or beneath a cover of superficial deposits (*drift*)

Brackish water Slightly salty water (including groundwater); formed when fresh river water dilutes sea water in an estuary

Braided river A river in which many constantly shifting, sinuous and interweaving channels separate islands of *alluvium* which are covered during periods of flood

Braidplain The active depositional belt of a *braided river* or stream

Buried channel (or valley) An old channel or valley now filled by drift deposits

Clast An individual grain or rock fragment, normally a component of a *sediment* or *sedimentary rock*

Cleavage Parallel, closely spaced planes of weakness in rock, along which it splits easily; the result of tectonic compression

Cohesive A sticky *soil* such as clay

Conglomerate A coarse-grained sedimentary rock with average *clast* size greater than 4 mm

Cross-bedding Structure in sedimentary rocks comprising intersecting *bedding* planes

Cryoturbation General effects of frost disturbance in soils and rocks due to processes such as heave, slippage and freeze-thaw action; important in glacial and periglacial settings (also cryoturbated)

Delta Body of *sediment* formed at the mouth of a river or stream where it enters a lake or the sea

Diamict Poorly sorted deposit (soil) in which clasts of a variety of sizes are set in a finer clay matrix; normally applied to *till* (broadly synonymous with boulder clay)

Dip The angle or direction of inclination of planar surfaces (e.g. *bedding, cleavage*) in relation to the horizontal

Drift A general term for all unconsolidated superficial deposits of Quaternary age, which are distinguished from solid rocks; used on geological maps (hence drift map; drift deposits)

Dropstones Anomalously large *clasts* in a generally fine-grained marine or lake sediment which are most commonly derived (dropped) from floating masses of ice (icebergs)

Fault A surface or narrow zone of fracture, normally in rock, along which movement has occurred

Field slip The base map on which geological observations are recorded in the field

Formation The main unit of subdivision of a *sedimentary rock* succession which has internal characteristics which distinguish it from adjacent formations

Geotechnical Specialised geological data and methods used in assessment and solution of engineering problems

Glacial Pertaining to a glacier or ice sheet

Glaciofluvial Pertaining to the deposits and processes of rivers or streams which are intimately associated with glaciers or ice sheets, and which may flow beneath, within, on top, to the side or in front of the ice

Glaciolacustrine Pertaining to the deposits and processes in lakes associated with glaciers or ice sheets; such lakes may be beneath, within, on top, to the side or in front of the ice

Glaciomarine Pertaining to the deposits and processes of the sea where it is in close proximity to glaciers and ice sheets

Grain Mineral particle in sediment or *sedimentary rock*; largely synonymous with *clast*, but usually used for particles of sand grade size or less

Graptolite An extinct, tube-like organism which floated in the sea and fossils of which are used to date Lower Palaeozoic rocks

Gravel An unconsolidated accumulation of normally rounded *clasts* with average grain size greater than 4 mm

Groundwater Water contained in soil or rock

Group Broad unit of subdivision of a sedimentary rock succession; normally made up of two or more *formations*, but also used informally where formational subdivisions have not been finalised

Hydrogeology The study of geological factors which have a bearing on the movement, composition and exploitation of *groundwaters*

Isostatic rebound Process where by the Earth's crust (land surface) rises folowing the removal of a thick overburden, such as an ice sheet

Kame Moundy or bench-like landform left following the retreat of a glacier or ice sheet, typically composed of *glaciofluvial* deposits, which accumulated at the side or in front of the melting ice (also kamiform and kame terrace)

Kettle holes Steep sided depressions in *glacial* deposits, commonly partially filled by lacustrine clays and peat; formed by the burial of wasting ice masses such that as the ice melts the ground above collapses and ponds commonly form in the resulting hollow.

Lacustrine Pertaining to lakes and ponds

Laminae *Bedding* layers which are less than 20 mm thick (also lamination)

Lithology Rock type

Lodgement till A *till* formed beneath a glacier or ice sheet and which is commonly *overconsolidated*

Meandering river Highly sinuous river which occupies a single channel within a broad floodplain; over time the river migrates across the entire width of its floodplain

Melt-out till A *till* deposited directly from melting ice; the material carried within or on top of a glacier or ice sheet which is left behind on the land surface as the ice melts (synonymous with ablation till)

Misfit A river or stream which is too small to have cut the valley in which it flows; this implies that the river or stream was once much larger

Mudstone A *sedimentary* rock comprising mainly very fine particles (clay and silt grade); when used informally can include siltstones and thin sandstones.

Outwash *Glaciofluvial* deposits deposited by sediment laden glacial melt-waters

Overconsolidated Normally applied to a clay (soil) that has undergone greater compaction than its present position suggests, because the compacting agent (e.g. a thick ice sheet) is no longer present

Particle size distribution The percentage of particles in each size fraction of a sample of *soil*, *sediment* or *rock* ascertained by particle size analysis

Periglacial Pertaining to processes and settings adjacent to glaciers and ice sheets in which freeze-thaw action is important (see also *tundra*)

Permeability The property or capacity of *sediment* or *rock* to allow fluid (e.g. groundwater) to pass through it

Pingos Distinctive circular or irregular depressions surrounded by narrow ridges which form in *periglacial* settings and are now commonly partially filled by lake deposits or peat

Plate tectonics Process and results of forces deep within the Earth which move and fracture continental masses; the splitting of continents leads to the formation and growth of oceans; the collision of continents results in the uplift of mountain chains (orogeny)

Porosity The presence in *soil*, *sediment* or *rock* of voids (pore spaces), which may have the potential to be filled by fluid (e.g. groundwater)

Prodelta In front of a *delta*; used for *sediments* deposited in front of a delta as in prodelta muds

Proglacial In front of a glacier or ice sheet (as in proglacial lake)

Regolith In situ rubbly material (soil), largely composed of rock fragments, which occurs at the base of a weathering profile and which is transitional with *bedrock*

Retreat moraine Moundy accumulation of glacial material formed at the front of a glacier or ice sheet during a pause in its retreat (see also *kame*)

Rock (engineering) A natural material with a uniaxial compressive strength over a certain minimum value (usually taken as 1 MN/m^2), and composed of mineral grains

Rockhead The interface between unconsolidated superficial deposits (*drift*) and *bedrock* (usually taken at the base of weathering profiles in bedrock)

Running Property of unconsolidated, dry or water saturated, sand to flow as a fluid; significant in the context of excavation stability

Sand An unconsolidated sediment (*soil*) dominantly composed of grains (*clasts*) between 0.063 and 4 mm in average size

Sandstone A rock dominantly composed of grains (*clasts*) between 0.063 and 4 mm in average size

Sandur A *proglacial, outwash braidplain*

Sediment Unconsolidated material (*soil*) composed of mud, silt, sand or coarser particles (*clasts*)

Sedimentary rock Rock composed of cemented mud, silt, sand or coarser particles (hence *mudstone, siltstone, sandstone* and *conglomerate*)

Silt An unconsolidated sediment (*soil*) dominantly composed of grains (*clasts*) between 0.004 and 0.063 mm in average size

Siltstone A rock dominantly composed of grains (*clasts*) between 0.004 and 0.063 mm in average size

Soil (engineering) All material composed of aggregates of rock particles which can be separated by gentle means and excavated without blasting

Solid A general term for the geology of solid rocks (bedrock), as distinguished from *drift* deposits; commonly used on geological maps (hence solid map; solid geology)

Solifluction A process involving the slow downslope movement of superficial materials (*soils*) as a result of the alternate freezing and thawing of the contained water; typical of periglacial settings

Strike The orientation of a horizontal line drawn on a vertical or inclined surface such as a bedding or cleavage plane

Subglacial Said of processes which operate, or features which form under an ice sheet or glacier

Superficial deposits Unconsolidated glacial and post-glacial *sediments* and *soils* (*drift*)

Till A deposit (*soil*) derived directly from ice, typically comprising a stiff clay in which rock clasts of a wide variety of sizes are distributed (*boulder clay* or *diamict*), but also including gravelly clay (see also *lodgement till* and *melt-out till*)

Tundra *Periglacial* region or condition in which soils contain a permanently frozen layer (permafrost)

Turbidite The deposit of a turbidity current, which is a turbulent mixture of sediment and water, which flows on the sea floor under the influence of gravity

Varves Alternating clay and silt-rich *laminae* characteristic of *glaciolacustrine* deposits and recording the seasonal variations in the supply of sediment to lakes in glacial (or *proglacial*) settings

Vein A mineral infilling of a fault or fracture in rock

Well sorted Pertaining to a sediment (*soil*) or sedimentary rock in which most of the constituent grains are approximately the same size

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