

Gower Peninsula—Coastal Diversity, Debated Pleistocene Impacts, Bedrock Structural Control and Long-Term Geomorphological Legacy

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Abstract

Within its area of c. 180 km², Gower Peninsula in south Wales has a rich and diverse array of geomorphological highlights that include past and present coastal landforms and processes, long-term geomorphological development, karst features, effects of Quaternary environmental changes including fossil beaches and platforms, and glacial and periglacial landforms and sediments. The coastline is renowned for its spectacular cliffs, caves, bays, beaches and dunes. The configuration and gross morphology of Gower owe most to bedrock geology and structure together with the enduring effects of planation. Its location near the margin of the last ice sheet has resulted in a wealth of accessible glacial and periglacial sediments and landforms that have intrigued researchers since the nineteenth century and kept Gower at the forefront of reconstructing ice-sheet behaviour and extent in western Britain. Karst features are mostly isolated except at the coast, where caves and marine karren are common.

Keywords

South Wales • Planation surfaces • Coastal landforms • Interglacial shore platform and beach • Glaciation • Periglacial sediments • Karst

29.1 Introduction

The Gower Peninsula (Welsh: Penrhyn Gŵyr) is c. 180 km² in size and juts out westwards from the south Wales coastline into the Bristol Channel (Fig. 29.1). It is bounded to east and west, respectively by Swansea and Carmarthen bays,

and to the north by the Loughor Estuary (or Burry Inlet). From Worms Head in the west to Mumbles Head in the east, Gower measures c. 25 and c. 7–12 km north to south. In 1956, the peninsula was designated Britain's first Area of Outstanding Natural Beauty: on south and west coasts, it boasts spectacular, steep, rocky cliffs, caves, sandy bays and dunes. Bristol Channel tides are amongst the largest in the world; Swansea Bay has mean spring and neap tidal ranges, respectively, of c. 8.6 m and 4.1 m (Wilding and Collins 1980). In Rhossili (Welsh spelling: Rhosili), Threecliff (often written as Three Cliffs) and Oxwich bays, it has three renowned stretches of coastline. Whilst the north coast is less spectacular, its broad marshes nevertheless provide geomorphological interest. Inland, rural Gower is characterised mostly by commonland, pasture, arable farmland and woodland on lower terrain contrasting with rough grazing on rounded hills rising above it. This chapter takes the eastern limit of Gower as the 'neck' between the west of Swansea Bay and Loughor on the estuary of the same name.

The rich fossil human and mammalian cave remains first attracted scientific interest in Gower. Following Reverend William Buckland's famous discovery of a partial male skeleton (still popularly called the 'Red Lady of Paviland') in a west Gower cave (Buckland 1823), remains were excavated from many other caves. Cave accessibility and close juxtaposition with fossil beach sediments, glacial and locally derived diamicts and other Pleistocene sediments combined with opportunities to apply innovative dating techniques (especially amino acid ratios) has kept Gower in the forefront for unravelling Pleistocene chronology in western Britain (e.g. Campbell and Bowen 1989; Shakesby and Hiemstra 2015).

Interpretation of Pleistocene landforms has caused controversy. An early ice sheet extending to the southern shores of the Bristol Channel is widely accepted, but where the last ice sheet terminated in Gower has long been disputed. Focus on the Pleistocene has largely overshadowed findings associated with other geomorphological highlights of which

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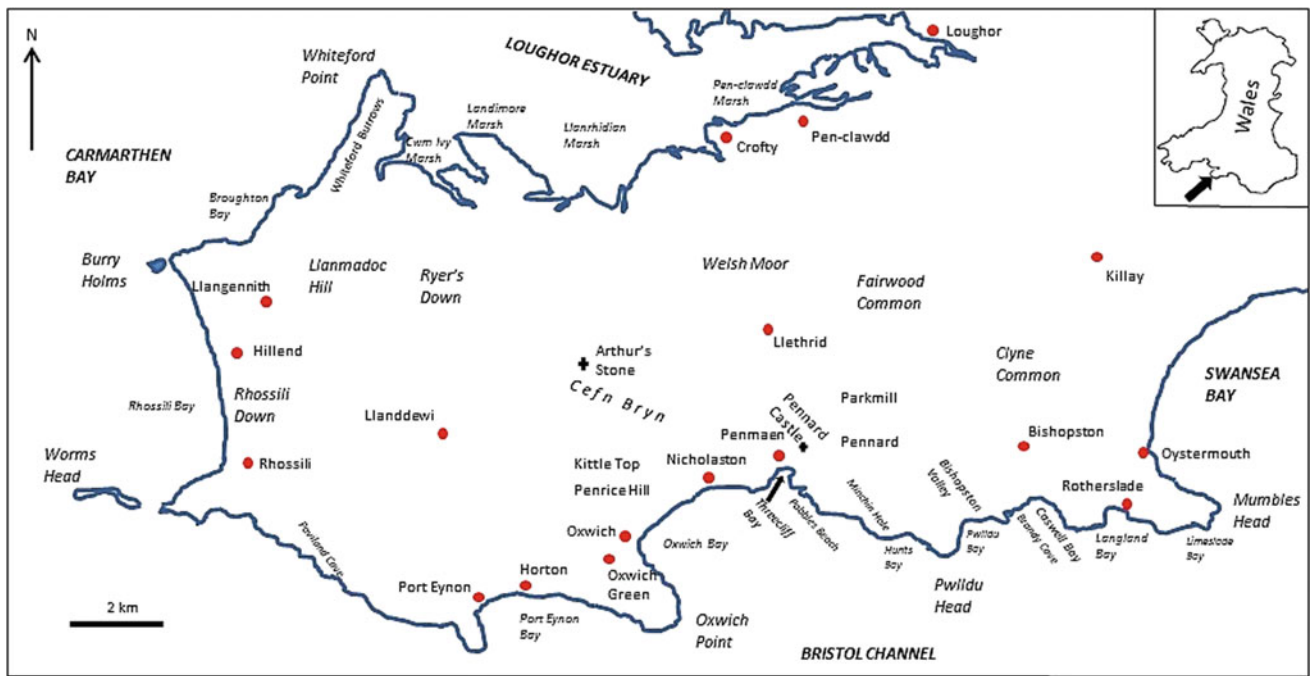


Fig. 29.1 Gower Peninsula with place names and features mentioned in the text. The location of Gower in Wales is indicated in the inset map

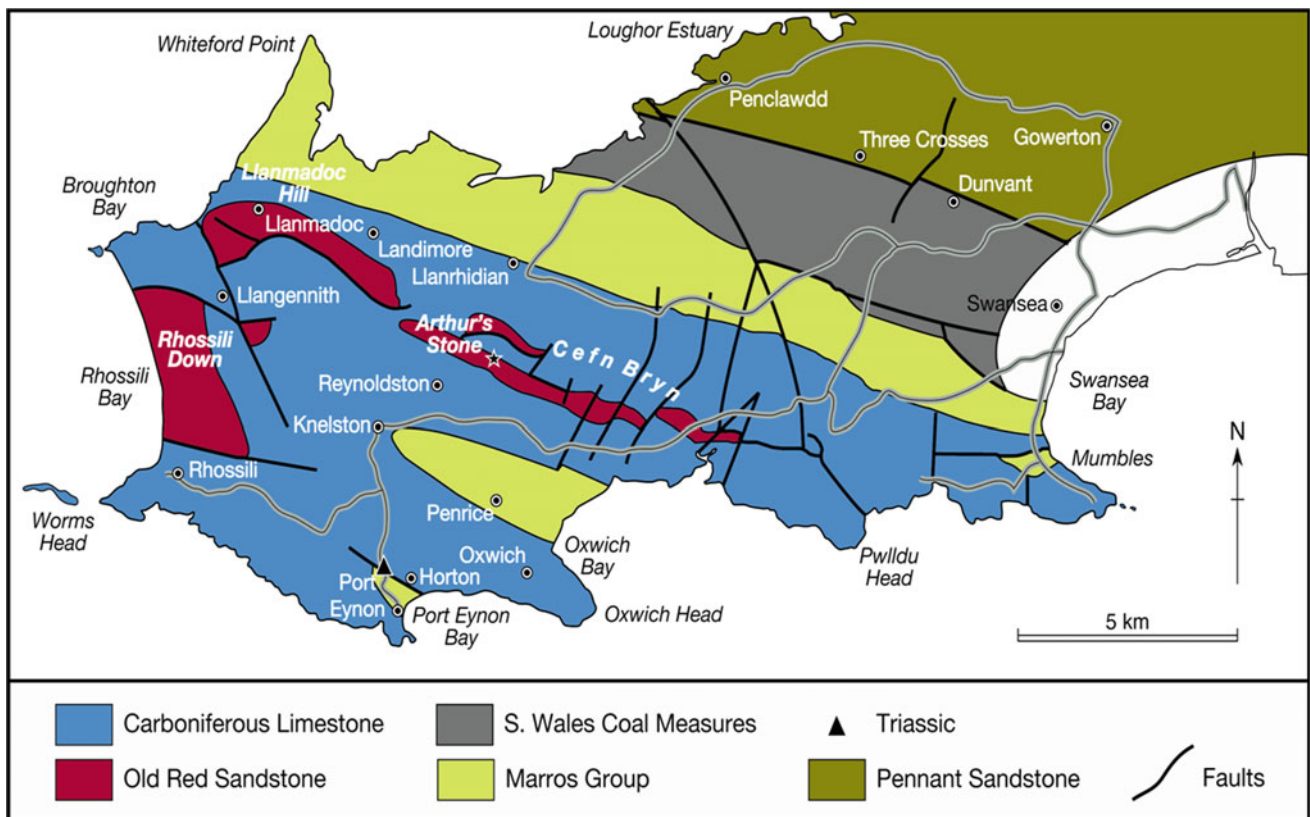


Fig. 29.2 Simplified geology of Gower. Grey lines represent roads. Reproduced from Shakesby RA, Hiemstra JF (eds) (2015) *The Quaternary of Gower. Field Guide* and published with kind permission of the Quaternary Research Association

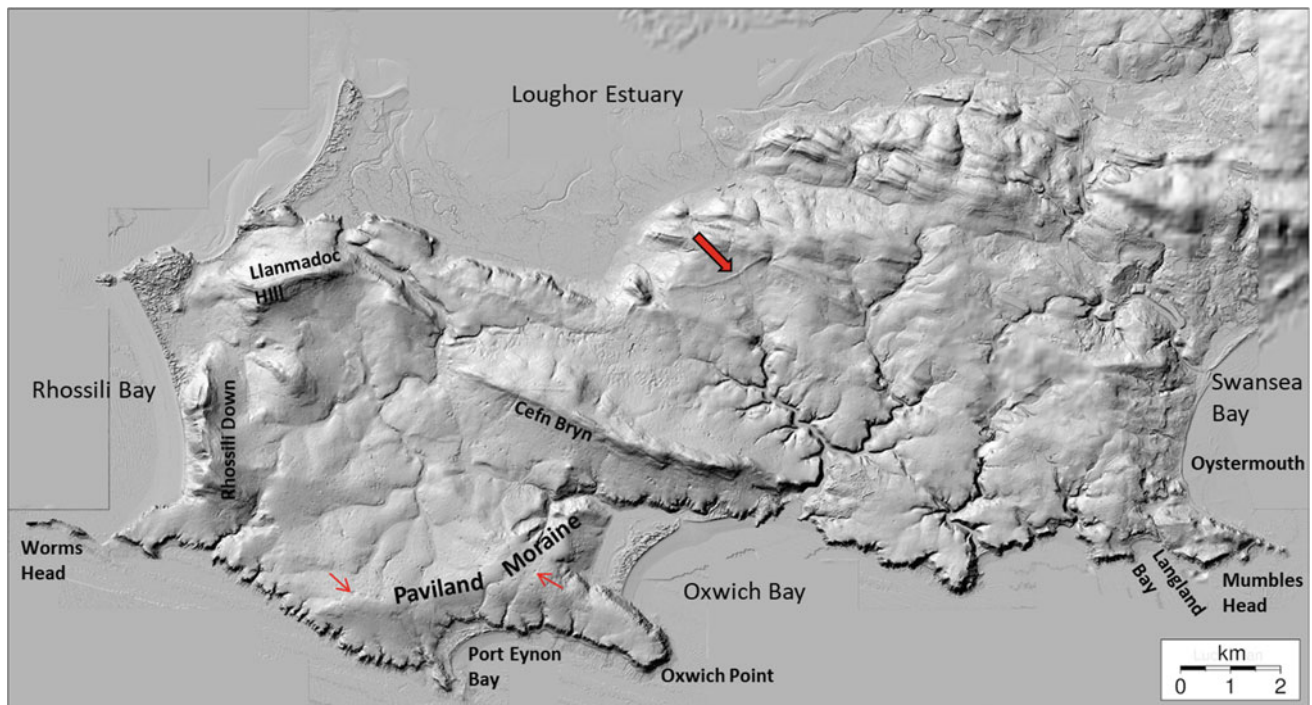


Fig. 29.3 Digital Elevation Model (DEM) of Gower. Paviland Moraine and Welsh Moor recessional moraine (large arrow) and two (of many) examples of small, near-circular depressions (small arrows) thought to represent sediment-infilled limestone cavern collapse

long-term landscape development, coastal processes, sediments and landforms, and karst landforms are examples.

29.2 Bedrock Geology and Structure

Bedrock geology and landscape show close affinities in Gower (Figs. 29.2 and 29.3). Large-scale folding accounts for the distribution of rock types and has strongly influenced the broad coastal configuration and inland topography (Owen 2015). Rocks comprise almost entirely Upper Palaeozoic strata: mainly Devonian Old Red Sandstone, early Carboniferous (Dinantian) Limestone and late Carboniferous (Namurian) Marros Group (formerly ‘Millstone Grit’), and Westphalian Coal Measures and Pennant Sandstone (Table 29.1). Much of south Gower comprises Carboniferous Limestone, with excellent cliff but few inland exposures. Old Red Sandstone in the cores of the anticlines projects above the limestone as rounded hills and ridges. In situ Mesozoic rocks are restricted to Triassic conglomerates and breccias at Port Eynon. In addition, Keuper marl and breccia of possible Triassic age occur in faults and fractures, for example in Rotherslade Bay, suggesting once more extensive Triassic deposition (Owen 1971).

Opinion has differed concerning the former existence of Jurassic and Cretaceous covers (see Cope 1984). There is some support in thick offshore successions of these rocks

features are shown together with key locations referred to in Sect. 29.2. ©Environment Agency. *Contains public sector information licensed under the Open Government Licence v3.0* (<http://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/>)

around Wales, Liassic bedrock in the Bristol Channel (Owen and Bridges 1980), an early Jurassic fossil in Pleistocene head (Smith et al. 2002) and a Liassic erratic (Strahan 1907). Battiau-Queney (1984), however, regarded subsequent, virtually complete stripping of these rocks as improbable.

During the late Carboniferous Variscan Orogeny, intense buckling created ESE–WNW folds, forming anticlines at Cefn Bryn, Llanmadoc Hill, Oxwich Point, Rhossili Down, Worms Head and Langland-Mumbles Head, and beds dipping from $<20^\circ$ to near-vertical (Fig. 29.3). Synclines include those at Oxwich, Port Eynon and Oystermouth. Folding was accompanied by parallel thrusting and cross-faulting, which mostly reflect extensional deformation, though many faults include strike-slip movement (George 1940; Owen 2015). Marine erosion of the resulting fractures has produced south coast rocky bays at, for example, Limeslade, Langland, Caswell, Brandy Cove and Threecliff: broader bays coincide with less resistant Namurian shales in synclines at Oxwich and Port Eynon.

29.3 Planation Surfaces

Views along the south coast cliffs would convince the most sceptical geomorphologist that planation (erosion) surfaces exist (Figs. 29.4 and 29.5). Together with parts of Pembrokeshire and Vale of Glamorgan coasts, roughly accordant

Table 29.1 Geological succession and selected events in Gower

Age (Ma)	Period	Epoch	Events in Gower
0.0117	Quaternary	Holocene	See Table 29.3
2.59		Pleistocene	
23.03	Neogene	Pliocene	Planation surfaces produced by marine processes?
		Miocene	
66.0	Palaeogene	Oligocene	Uplift. Erosion of Cretaceous and Jurassic rocks?
		Eocene	
		Palaeocene	
145	Cretaceous		High sea level at times. Chalk cover deposited?
201	Mesozoic	Jurassic	High sea level at times. Marine sediments deposited around coast of Wales and in Gower?
252		Triassic	In situ rocks in Gower now limited to Port Eynon syncline. Planation surfaces formed by subaerial processes?
299	Palaeozoic	Permian	Planation surfaces formed by subaerial processes?
359		Late Carboniferous	Variscan deformation causing folding and faulting Marros Group, South Wales Coal Measures and Pennant Sandstone mudstones, sandstones and conglomerates
		Early Carboniferous	Dinantian Carboniferous Limestone deposited
419		Devonian	Old Red Sandstone deposited

Note that dates refer to lower boundaries of periods

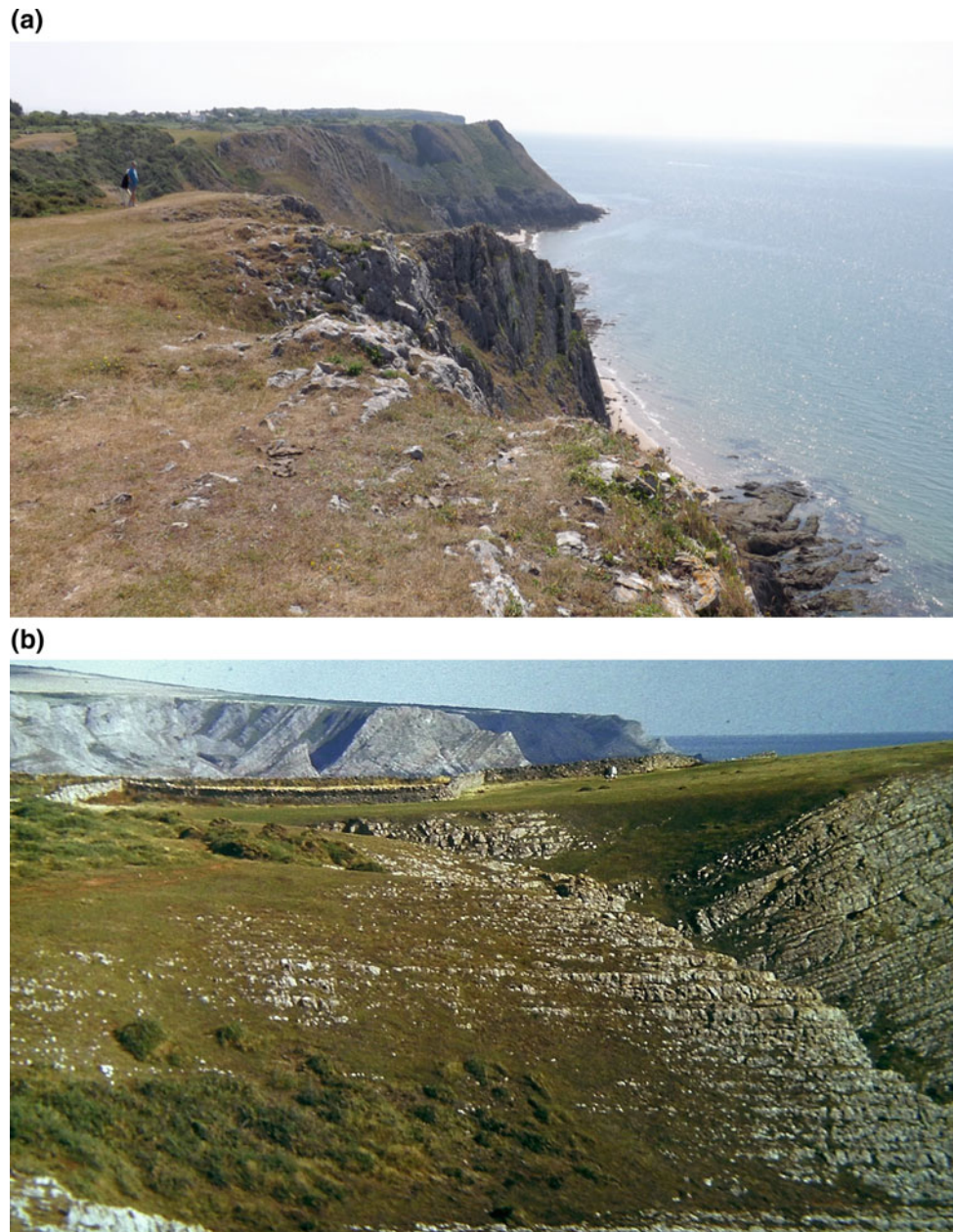
Fig. 29.4 Oblique aerial view looking eastwards across the 60-m planation surface near Rhossili. The surface ends abruptly in steep cliffs. (The elongated fields in the foreground form part of The Vile medieval open-field system.) © GRH Gower Society



summits and relatively flat ground forming abrupt junctions with higher ground attracted interest and debate for more than 100 years (e.g. Ramsay 1846; Goskar and Trueman 1934; Brown 1960). In Britain, from the 1960s until recently, however, denudation chronology, which aimed to assign origins and ages to surfaces, was replaced by a paradigm focusing on observable processes. Interest in

chronology was diverted to Quaternary science. Geomorphological research in Gower clearly charts this paradigm shift, with interpretation of Quaternary landforms, sediments and chronology dominating since the late 1960s. Arguably, however, planation together with bedrock geology has contributed more to Gower's landscape than changes caused by repeated Quaternary glacial and periglacial episodes.

Fig. 29.5 The 60-m planation surface on the south Gower coast. **a** Looking eastwards from near Pobbles Bay; **b** Looking east from near Rhossili across variably dipping Carboniferous Limestone strata. (Photos R. A. Shakesby)

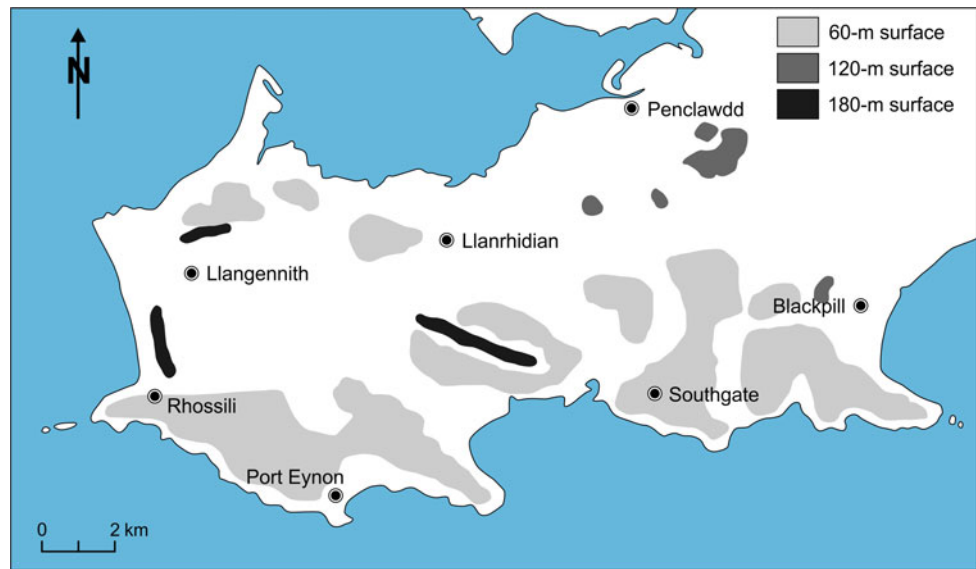


The limestone cliff-line on the south coast is interrupted by two relatively large, partially dry valley systems (Pennard Pill and its tributary streams and Bishopston Valley), synclinal and fault-guided bays and short dry valleys. The intervening cliff tops show height accordance irrespective of folds and strata dipping at different angles. These cliff-top sections are parts of a 60-m (so-called ‘200-foot’) surface, which ends abruptly at the cliffs along south Gower. Some height variation occurs, the surface rising smoothly, for example, to c. 90 m between Pennard and Pwlldu Head, and falling to c. 50 m from Rhossili towards Worms Head. Two other proposed surfaces—the 120 m (‘400-foot’) and 180 m (‘600-foot’)—are far less extensive (Fig. 29.6). The former

is confined mainly to shales and sandstones in the east. The 180-m surface is represented by the Old Red Sandstone anticlinal cores of Llanmadoc Hill (186 m), Cefn Bryn (188 m) and Rhossili Down (193 m). The summits correspond to strata of different resistance, supporting an erosional rather than geological explanation of their accordant heights (George 1938).

A marine origin for the Gower surfaces has had overwhelming support (e.g. Goskar and Trueman 1934; Brown 1960; George 1974). Although lacking marine sediments, this origin was thought to be supported by the independence of rock structure, presumed marine morphological characteristics (low relief, gentle seaward gradient), stepped form

Fig. 29.6 The 60-, 120- and 180-m planation surfaces according to various authors



attributed to pulsed uplift and falling sea level, and constant height at the reconstructed inland fossil cliff-foot. There are problems with a marine origin including: (1) requirement of rapid relative sea level fall followed by a slow restricted rise to allow marine abrasion to erode surfaces to widths of $>c.$ 1.2 km (King 1963), without freeze-thaw or other highly effective erosion processes, although freeze-thaw would imply glaciations and glacio-eustatically lowered sea level; (2) the survival of unconsolidated terrestrial deposits pre-dating the most popular age for marine planation (Walsh et al. 1987, 1999; see below); and (3) the narrowness of the interglacial shore platform (s) around Gower. Unpublished bathymetric data also suggest the modern shore platform is much narrower than the 60-m surface (John Cooper, pers. comm.). Alternative, terrestrial origins—peneplanation, pediplanation and etchplanation—were mostly not contemplated for Gower surfaces, though they have been for similar ones elsewhere in south west Britain (e.g. Walsh et al. 1987, 1999), and Battiau-Queney (1984, 1999) viewed all Welsh surfaces as Palaeogene or earlier etchplains surviving on stable blocks. Marine planation in Britain has, nevertheless, seen recent renewed interest (e.g. Westaway 2009).

Few clues about dating and a hypothesised land uplift have led to assumed increasing age with increasing height (Owen and Bridges 1980), which certainly accords with less extensive 120- and 180- than 60-m surfaces. Pliocene has been the most popular formation date (e.g. George 1938; North 1955), although early Mesozoic (Strahan 1907), sub-Mesozoic (Smith et al. 2002) and early Pleistocene interglacials (Brown 1960; Bowen 1994) have also been considered. Bowen (1994) took the height of last interglacial beach sediment as +10 m OD around Gower and the corresponding global sea level as $c.$ +6 m. From the height difference, and therefore uplift implied for Gower since that

time, Bowen regarded early Pleistocene interglacial dates for the 60- and 120-m surfaces as feasible. Problems with an early Pleistocene marine origin include no marine sediments on the planation surfaces, in contrast to last interglacial shorelines where they are common, and the narrowness of known interglacial shoreline remnants and of the current shore platform. Of relevance, unconsolidated Oligocene and Miocene sediments on similar surfaces in south west England and Pembrokeshire indicate at least a part Palaeogene/Neogene boundary age for the underlying platform. If any subsequent marine inundation did occur, its impact on easily eroded sediments would have to have been minimal (Walsh et al. 1987, 1999). A lack of appreciable warping of surfaces has been viewed as evidence of Pliocene or later formation given strong Oligocene and Miocene earth movements. In addition, estimating the last interglacial sea level from Gower beach remnant heights is difficult because of their wide height range (see below), and other estimates of last interglacial sea level tend to be somewhat less than +10 m (e.g. Dutton and Lambeck 2012). The revival of interest in long-term geomorphological development may help to resolve questions of the ages and mode of formation of the surfaces.

29.4 Limestone: Karst Landforms and Denudation Rates

Karst landscape features are less prominent in Gower than might be expected given the dominance of limestone. With notable exceptions, they are mostly restricted to the coast or they form isolated examples (Ede and Bull 1989). Exceptions include, first, a classic limestone drainage pattern north of Cefn Bryn, where runoff from impermeable Old Red

Fig. 29.7 Well developed microkarst in the mid-tide zone in the foreground, Worms Head. Barnacles cover the rock surfaces. Microkarst is less well developed near low tide level in the background. (Photo R. A. Shakesby)



Sandstone sinks into limestone, re-emerging along the north Gower marsh edge. Second, over a short distance, Bishopston Valley has sink, collapsed cavern and resurgence features. Its incised nature has been linked to glacial times when low sea level combined with sediment-blocked fissures and caves and frozen subsoil would have impeded infiltration promoting surface rather than subsurface flow of meltwater (Crowther 1989). Other steep-sided valleys on limestone probably had similar origins. Third, the limestone cliffs have numerous, short (mostly <60–70 m) caves. According to Ede and Bull (1989), only two inland cave systems of significant length exist, both in the Llethrid (or Llethryd)-Parkmill valley, although they suspected there might be another in the Bishopston Valley.

Fourth, limestone rocky shorelines have well developed marine karren between low tide and the spray zone above high tide level (Fig. 29.7). These microkarst features comprise cm- to m-scale pools, pits and passages, together with positive forms which, at their extremes, are jagged and arête-like. Ley (1979) found that maximum internal relief occurred just below mid-tide height and attenuated towards the tidal extremes. He thought they formed by solution, quarrying and abrasion, which are maximised in the mid-tide zone. Jennings (1985), however, reasoned that seawater would be saturated with calcium carbonate and that a biochemical process was required for solution to occur. Nocturnal lowering of pH took place, he argued, through increased carbon dioxide emission by algae and invertebrates, thus promoting solution. Other likely processes

include wetting and drying causing mechanical breakdown and grazing, browsing, rasping and burrowing by various invertebrates (Bird 2000). Fifth, often hidden from view are depressions up to tens of metres across, some filled with water and others artificially modified, that ‘pockmark’ much of west Gower where glacial sediment, particularly on the Paviland Moraine, has slumped into limestone collapse features to form bowl-like depressions (Fig. 29.3).

In Table 29.2, several short- and long-term published and unpublished denudation rates for Carboniferous Limestone in Gower and elsewhere in south Wales are compared with rates determined by different methods for limestone in northern England. The 11.3 mm/1000 years erosion rate for the Gower cliff-top site, based on some 30 years of monitoring using a micro-erosion meter, is similar in magnitude to figures based on both this and other methods in Gower and elsewhere. Rates for the spray and intertidal zones around Gower’s coast, not surprisingly, are higher reflecting the dominance, respectively, of bio-erosion producing a pitted surface and abrasion creating a smooth surface.

29.5 Quaternary Environmental Change, Sediments and Landforms

Coastal exposures of Quaternary deposits in cliff-foot and dry valley mouth positions typically display one or more of the following sedimentary units: fossil beach sediment resting on limestone overlain by sands and/or silty sands,

Table 29.2 Rates of limestone erosion for sites in Gower, south Wales and northern England using a variety of monitoring and long-term estimation techniques

Location	Method	Monitoring period	Erosion rate (mm/1000 yrs)	Source
<i>Monitoring</i>				
Oxwich Point, Gower (cliff-top)	Micro-erosion meter	30.5 years	11.3	Unpublished data (see Shakesby and Walsh (1986) for description of sites)
Oxwich Point, Gower (spray zone)	Micro-erosion meter	30.5 years	42.0	Unpublished data (see Shakesby and Walsh (1986) for description of sites)
Oxwich Point, Gower (intertidal zone)	Micro-erosion meter	30.5 years	81.9	Unpublished data (see Shakesby and Walsh (1986) for description of sites)
Burry catchment, Gower	Solute load	1 year	29.8	Chambers (1983)
Mellte catchment, South Wales Coalfield	Solute load	1 year	15.8	Groom and Williams (1965)
Malham, N. Yorks.	Micro-erosion meter	2–5.5 years	10–50	Trudgill (1986)
<i>Long-term estimation</i>				
North Crop, South Wales Coalfield	Lowering of rock relative to glacially abraded surface	–	25–75 ^a	Thomas (1970)
Yorkshire Dales, England	Glacial erratic pedestal height	–	34	Huddart (2002)
Yorkshire Dales, England	Glacial erratic pedestal height	–	3–13	Goldie (2005)
Limestone pavement, Yorks.	Cosmogenic ³⁶ Cl	–	18.3 ^b	Wilson et al. (2012)

^aVarying rate depending on lithology

^bAssuming a starting date of 18,000 years ago and dissolution with no mechanical weathering

diamicts containing locally derived and/or far-travelled clasts capped by a mainly silt layer. The nature and possible origins of these units are presented in this section.

29.5.1 Sea Level

Both interglacial shore platform remnants and (mostly) cemented interglacial beach deposits can be found between about 0 and +15 m OD along the south coast (Figs. 29.8 and 29.9). More than one platform has been proposed, though this is not evident in Fig. 29.8b. Fossil beach sediments typically contain subangular to rounded, mostly limestone clasts with occasional, mostly Coalfield erratics, together with sand and whole and broken marine shells of common modern species (notably *Patella vulgata*; Fig. 29.9b). The proposed numbers of sea level events, types of environment and ages have varied. Prestwich (1892) suggested a single beach post-dating the ‘glacial drift’. Strahan (1907) likewise

favoured one beach, but pre- rather than post-dating the ‘glacial drift’. George (1932) proposed three separate beaches distinguished by height and shell species. The oldest and highest was the *Patella* beach, followed by the *Neritoides* beach (named after the characteristic shell species) and, cemented to the modern shore platform, the Heather-slade beach was distinguished by large boulders and relatively common erratics. Occasional erratics in the *Patella* beach led George (1932, p. 295) to suggest formation during ‘incipient glaciation’ when valley glaciers ‘broke into floes’. The *Neritoides* beach, in contrast, was assigned to a warm interlude and the Heatherslade to the Neolithic. Subsequently, Mitchell (1960) and Bowen (1970) recognised only one (interglacial) beach, though disagreeing over its age. The application of amino acid ratios (AARs) in the 1980s to beach shells led to new interpretations. Bowen and co-researchers interpreted the AARs as representing more than one interglacial (e.g. Davies 1983; Bowen et al. 1985; Bowen and Sykes 1988), but data treatment was later shown

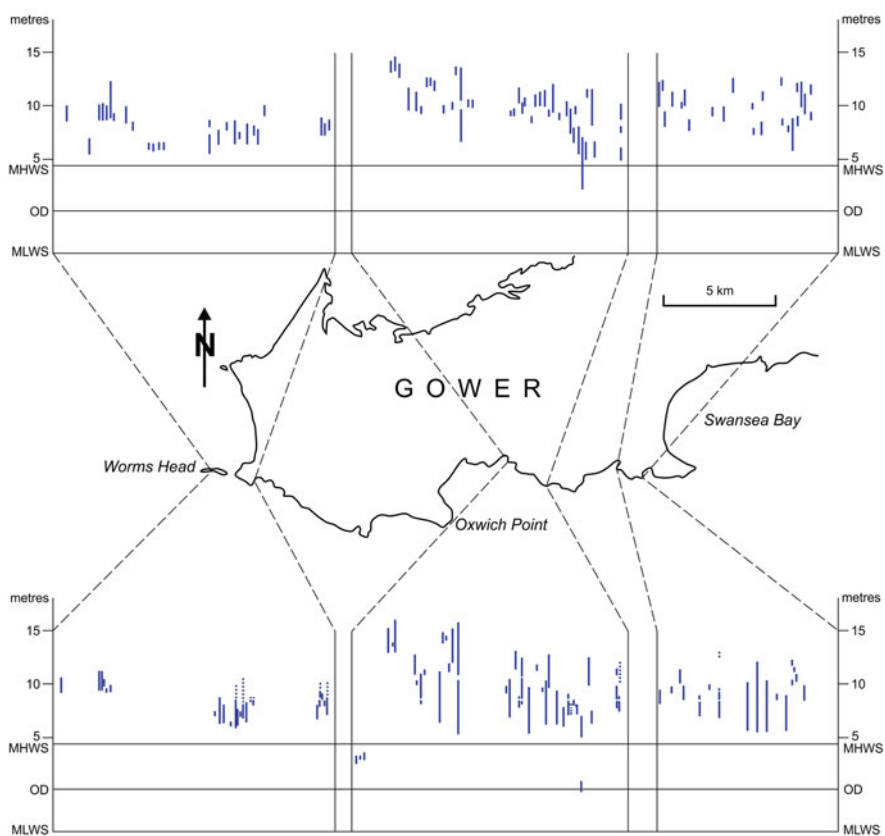
Fig. 29.8 **a** Interglacial shore platform cut across southward-dipping Carboniferous Limestone beds east of Brandy Cove. The platform is backed by a terrace comprising Pleistocene deposits (Photo R. A. Shakesby); **b** Height ranges of interglacial rock platform remnants (upper) and fossil beach deposits (lower). (MHWS = Mean High Water Spring tides; MLWS = Mean Low Water Spring tides; OD = Ordnance Datum). From an unpublished manuscript by G. E. Groom

(a)



(b)

(A) Height ranges of some raised beach platforms



(B) Height ranges of some fossil beach deposits

From an unpublished manuscript
by the late Miss G.E. Groom

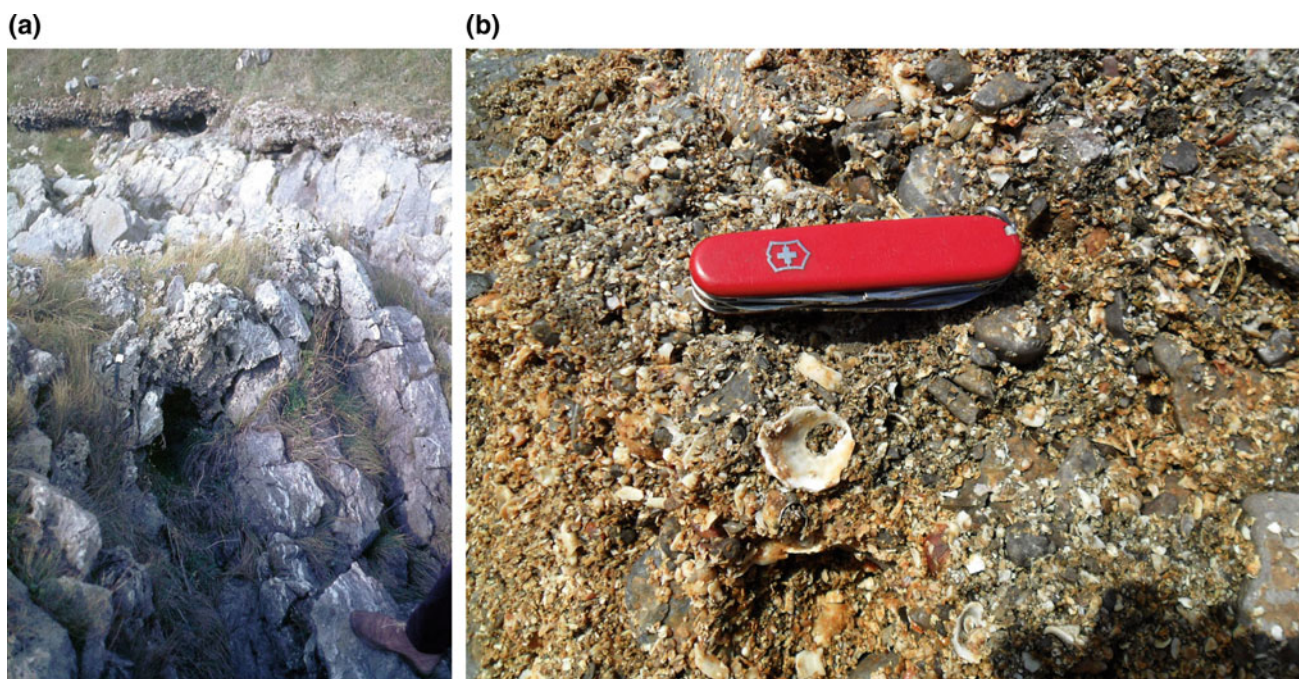


Fig. 29.9 **a** Cemented interglacial beach resting on the raised limestone platform near Brandy Cove shown in Fig. 29.8a; **b** Close-up view near Oxwich Point of cemented interglacial beach,

comprising sand, pebbles and fragments of marine shells including a nearly intact common limpet (*Patella vulgata*) shell. (Photos R. A. Shakesby)

to be invalid (McCarroll 2002). Experimental application of a revised AAR technique has shown promise (Demarchi 2009), but has yet to be applied systematically around Gower. In Minchin Hole Cave, there are two superimposed beaches, so that the idea of two distinct sea level events remains valid, though they might both date from the last rather than two separate interglacials (Andrews et al. 1979).

Locally, evidence for rapid sea level rise in the first half of the Holocene lies below present sea level (Culver 1977; Pye and Blott 2010), but terrestrial organic remains (e.g. peat and tree trunks and roots) exposed at low tide, and marine clays, together with now truncated, eroded, cliff-foot terraces and fans of Pleistocene sediments in coastal dry valleys (known locally as slades) (Fig. 29.10) attest to continuing sea level rise up to the present day. Most researchers have suggested a smooth, declining rate of sea level rise since the mid-Holocene (e.g. Shennan and Horton 2002), but possible small oscillations around the present level (Edwards 2006) or rise to as much as +4.5 m OD in south Wales have been suggested (Bowen 1970).

29.5.2 Periglaciation

The main contribution of periglacial action to Gower's landscape, as in many other areas subject to cold tundra-like conditions, has been relief reduction, which is illustrated by the vestiges of this relief reduction process seen in the

remnant terraces and dry valley fans of Pleistocene deposits referred to above (Fig. 29.10). In addition to proglacial and paraglacial input to these sediment accumulations (see below), the periglacial contribution is thought to be as follows. Deposited in patches on bedrock or fossil beach sediment, where present, is a reddish sand assumed to have been wind-eroded from the exposed sea-floor as sea level fell early in the last glaciation, but more commonly there is a mainly sandy-silt deposit, sometimes with sub-parallel strings of Coalfield erratic pebbles and granules interpreted as a periglacially redistributed soil formed in the preceding interglacial (Bowen 1970). Case (1993), however, argued that similar sediment in Hunts Bay was in situ Early Devensian soil.

Overlying and interdigitating with this unit there is often a diamict typically up to c. 10 m thick comprising angular clasts of the local bedrock (limestone along the south coast and Old Red Sandstone downslope of Rhossili Down) set in a sand-silt matrix. Elongated clasts typically show a strong downslope preferred orientation, reflecting a classic solifluction origin. In limestone coastal dry valley fans, this single-lithology diamict dominates exposures either side of the valley axis where it is replaced by a characteristic wholly glacigenic diamict (see next section for its origin). These two diamicts often have a sharp contact, though there are also often additional patches of diamict containing a mix of glacigenic and locally derived limestone clasts. These three diamicts were viewed by Bowen (1970) as periglacial

Fig. 29.10 Examples of **a** an eroded terrace consisting of Pleistocene deposits at the foot of Rhossili Down in Rhossili Bay, and **b** the remnant of a fan of Pleistocene deposits infilling the dry valley in Hunts Bay. Such deposits occur around much of the south and west cliffed coastline and would have been far more extensive when they formed in glacio-eustatically lowered sea level during the last glaciation. (Photos R. A. Shakesby)



deposits ('head'): limestone-dominant and mixed limestone and Coalfield diamicts were both thought to have been derived mainly by solifluction whilst the glacial unit had been affected also by snowmelt alluvial action (an alternative origin is described below). The sandy loam upper unit (c. 60% silt), usually up to c. 1 m thick, often contains a few pebbles including worked flints, suggesting a two-stage origin by wind erosion of glacial outwash sediments during either continued low sea level soon after ice wastage or, less likely given no sign of a hiatus, in the later Younger Dryas Stadial (12.9–11.7 ka), followed by hillwash reworking (Case 1977) in the Holocene (Table 29.3).

In a few coastal exposures, post-depositional churning of the diamicts and upper loessic sediment is evident in the re-arrangement of units, clasts and sediment bedding. In Fig. 29.11, relatively regular structures up to >1 m in amplitude, match the description for type 2 cryoturbations provided by Vandenberghe (2013). These features can apparently form in different combinations of sediment texture. If segregated ice lenses preferentially formed in the coarse, lower layer in Fig. 29.11, in response to the drainage barrier formed by the underlying impermeable permafrost, density would be reduced. On melting, liquefaction would occur and loading by the overlying, less saturated and thus denser fine

Table 29.3 Quaternary geomorphological developments in Gower. See text for elaboration and disputes concerning timing and effects of events

Event	Marine Isotope Stage	Approx. age (yrs BP)*	Quaternary stages	Sea level status	Climate	Geomorphological developments in Gower
Flandrian	1	11,700 12,900 c. 14,700	Holocene	Sea-level rise to present height, (possibly above?)	Temperate	Sand blowing in Medieval times Sand dune, marsh and peat development at the coast. Surface stabilisation. Soil development
Younger Dryas Stadial	2		Devensian	World sea-level fall to minimum of c. -120 m OD	Cold	Loessic sediment deposited?
Windermere Interstadial					Short temperate interlude	Surface stabilisation (no firm evidence in Gower)
Late Devensian glaciation (Last Glacial Maximum at c.22,000 yr BP)					Cold	Loessic sediment deposited following ice wastage? Ice sheet extends into Swansea and Carmarthen bays and impinges onto Gower. Exact limit subject to debate. Head deposited beyond ice limit.
Middle and Early Devensian	3	29,000			Cold, with short temperate interludes (interstadials)	Head deposited under periglacial conditions. Possible brief phases of surface stabilisation, but no evidence
	4	57,000				
	5a-d	71,000		Onshore wind-blowing of sand as sea-level falls		
Ipswichian Interglacial	5e	119,000	Ipswichian	High (globally, + 6-9 m OD**)	Temperate	Slightly warmer sea conditions than today. Fossil beach(es) formed 0-15m above OD (most were later cemented by percolating CaCO ₃ -rich groundwater). Surface stabilisation.
Wolstonian	6	130,000	Wolstonian	Low	Cold	Periglacial conditions, though no evidence
	7	191,000		High	Temperate	Surface stabilisation?
	8	243,000		Low	Cold	Periglacial conditions, though no firm evidence
Hoxnian Interglacial	9	300,000	Hoxnian	High	Temperate	Surface stabilisation?
Anglian Glaciation	12	474,000	Anglian	Low	Cold	Inundation of peninsula beneath ice sheet extending across Bristol Channel
Cromerian and Early Pleistocene	13-103			Alternating high and low sea level	Alternating temperate and cold episodes	Alternating periglacial and temperate conditions. Glaciation flowing from Irish Sea Basin during MIS 16(?). Planation surface(s) produced by marine action?
		2.59 mill.				

*Dates based on: Lisiecki LE, Raymo ME (2005) A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}\text{O}$ records. *Paleoceanography and Paleoclimatology* 20: PA1003

**Sea level estimate from: Dutton A, Lambeck K (2012) Ice volume and sea level during the last interglacial. *Science* 337: 216-219

Fig. 29.11 Deformation structures formed in mainly sandy-silt sediment (above) and clastic, limestone-dominant diamict (below) in an eroded terrace of Pleistocene sediments east of Oxwich Point. Correspondence of clast and lamination alignments with the boundary between the two sedimentary units suggests the structures may represent cryoturbations (rucksack resting on storm beach for scale). (Photo R A. Shakesby)



sediment would produce the type of distortion seen. If this interpretation is correct, formation must have occurred in a late deglaciation single event, otherwise annual freeze-thaw would have thoroughly mixed the sediments. Alternative origins are seismic activity or oversaturation caused by sub-surface water flow from the adjacent limestone cliffs, which would not have required permafrost (see Owen 1996).

29.5.3 Glaciation

Most glacial geomorphologists would accept that there is evidence of two glaciations during the Pleistocene—the Late Devensian (MIS 2, Last Glacial Maximum (LGM); c. 22,000 years ago), which moved southwards carrying South Wales Coalfield erratics, and an earlier event responsible for depositing erratics with an Irish Sea provenance (Table 29.3). Opinion would probably differ, however, about one or more other fundamental aspects of glaciation in Gower including: (1) whether there is morphological evidence of any other glaciation; (2) the date(s) of the pre-LGM glaciation(s); (3) the glacial limit(s); and (4) the depositional style of LGM ice (whether terrestrial or glacialmarine). Controversies have arisen largely because of: (1) a long-accepted scarcity or absence of indisputable ice-sheet terminal or recessional features; (2) limited and disputed dating evidence; (3) conflicting views about the origins of sediments; and (4) uncertainty about whether some clayey patches are interglacial palaeosol remnants.

In a landmark paper, Charlesworth (1929) used glacial depositional landforms as markers of the limit of ‘Newer Drift’ (i.e. LGM) ice in south Wales (Fig. 29.12). He identified ‘mounds of sand and gravel’ (no longer visible) extending westwards from Swansea to ‘Fairfield’ (Fairwood) Common and at ‘Bishopstown’ (Bishopston) in south-east Gower together with thick glacial sediment at Rother-slade to define the western limit in Gower of ice occupying Swansea Bay. Farther west in Gower, he thought, ‘marginal moraine’ (p. 346) was absent. Whilst there was a difference of opinion about the LGM limit across Gower, in most pre-1980 publications, Charlesworth’s Rother-slade limit on the south coast became a fixture (e.g. George 1933; Mitchell 1960,1972; Bowen 1970), and this view has continued for many researchers up to the present day (e.g. Clark et al. 2004; Cope and Bowen 2015). Rother-slade and coastal exposures to the east were assumed to include in situ LGM glacial sediment, whereas visually similar glacial sediment to the west was thought to be of pre-LGM age and removed by periglacial processes from the limestone plateau, as described in the previous section.

Moraine remnants and outwash were noted before 1980, but most were later overlooked or otherwise interpreted. Notably, Tiddeman (in Strahan 1907, p. 141) regarded an E–W aligned, arcuate ridge on Welsh Moor (Fig. 29.3) as ‘the terminal mark of a glacier or ice-sheet momentarily advancing during its retreat northwards’ (i.e. a recessional moraine in modern terminology). Bowen (1970; Fig. 9.1) mapped it as an esker, but its sandy-silt matrix, mainly

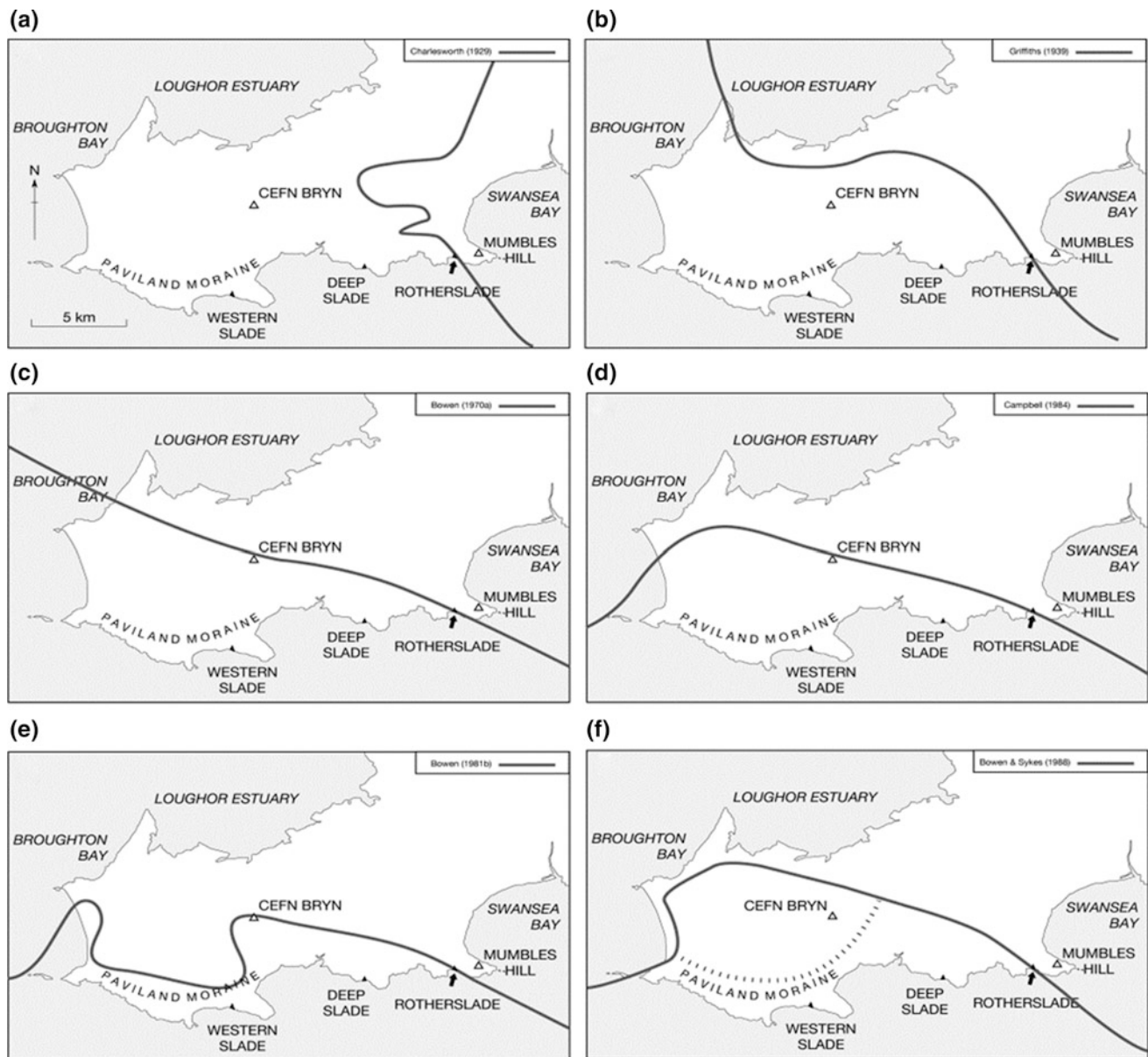


Fig. 29.12 Proposals for the last glacial maximum on Gower, 1929–1988: **a** Charlesworth (1929); **b** Griffiths (1939, 1940); **c** Bowen (1970); **d** Campbell (1984); **e** Bowen (1981); **f** Bowen and Sykes

(1988). Reproduced from Shakesby RA, Hiemstra JF (eds) (2015) *The Quaternary of Gower*. Field guide and published with kind permission of the Quaternary Research Association

subangular and subrounded clasts and arcuate shape favour Tiddeman's interpretation. This, however, implies N–S ice flow, which is at variance with E–W flowing LGM ice implicated by proposed end and/or recessional moraine fragments underlying Whiteford sand dunes, and also thought to occur at Crofty and at Loughor with counterparts on the estuary's northern shores (George 1938; Bowen 1980). Clear N–S clast preferred orientations and northern erratics in LGM glacitectorite in Broughton Bay in north-west Gower (Campbell et al. 1982; Campbell and Shakesby 1994, 2015) and Coalfield erratics on south-west Gower beaches (Bowen

2005) support N–S-moving ice. Resolving this conflict in ice flow directions is not easy: either there was a complex temporal interplay of lobes within the ice sheet moving in different directions or the interpretation of one or other ice flow direction is incorrect. In the latter eventuality, the clarity of the Welsh Moor moraine would imply that the E–W movement of ice is less likely. Surprisingly, perhaps, only one patch of outwash has been identified in Gower near Hillend in Rhossili Bay (Campbell and Shakesby 2015).

Although a 'glacial drift' cover in west Gower had long been accepted, only in the 1980s was there a report of a

substantial, arcuate end (or possibly recessional) moraine close to the south coast reported. Initially, it was mapped as LGM (Bowen 1981) but subsequently as pre-LGM in age (e.g. Bowen et al. 1985). This Paviland Moraine (Fig. 29.3) was formalised as a stratotype (Llanddewi Formation; Bowen 1999). Without dating evidence, its age was variously attributed to Marine Isotope Stages (MISs) 6, 8, 10 and 12 in different publications, although either a late Wolstonian (MIS 6; 191–130,000 years ago) or an Anglian Glaciation age (MIS 12; 478–334,000 years ago) was ultimately preferred because global ice volume was large during these glaciations (Bowen 2005) (Table 29.3). If Anglian, it would have been a recessional moraine of ice that earlier extended across the Bristol Channel (Gibbard et al. 2017). Bowen (2005) argued that its subdued form, highly weathered clasts and no superposition of moraine on interglacial beach sediment ruled out LGM formation. Shakesby et al. (2018), however, disagree and favour an LGM date, arguing that the subdued form of the moraine more likely reflects its mode of formation, moraine clasts are not exceptionally weathered and in situ moraine sediment is restricted to the limestone plateau and so would not be expected to be found overlying interglacial beach deposits in cliff-foot positions.

The precise extent and thickness variation of the Paviland Moraine remain unknown. The main part extends from west of Port Eynon Bay eastwards to Oxwich Green. Sediment cores reported briefly in Smith et al. (2002) included one from the moraine crest at 108 m OD, which showed at least 21.5 m of sediment overlying red clay. The moraine crest undulates and, given consistently dipping moraine sedimentary units in different cores they describe, Shakesby et al. (2018) propose formation primarily by ice-front proglacial sediment flows focused at intervals to create the high points along the crest.

From Oxwich Green, the moraine runs northwards to Cefn Bryn. This part is thicker (up to at least 60 m) and more dissected than the W–E section, with distinct hummocks at Penrice Hill and Kittle Top and proximal glaci-fluvial accumulations. Sparse glaciogenic sediment on Oxwich Point headland and in coastal exposures downslope of short dry valley mouths adjacent to the headland contrasts with the copious amounts in the Slade dry valley fan a short distance to the west and adjacent to the moraine, have led Shakesby et al. (2018) to favour an end rather than recessional moraine origin.

Although Rotherslade continues to be viewed by many as the western limit of LGM ice in south-east Gower, the similarity of the dry valley fan successions containing glaciogenic sediment east and west of Rotherslade casts doubt on this idea. A second problem is how unmixed glaciogenic sediment could reach dry valley fans following transport by periglacial processes generated in small or extremely small cliff-top catchments without becoming mixed *en route* with

easily entrained frost-weathered limestone debris. Third, where did LGM ice terminate across the peninsula between Rotherslade and north-west Gower where there is convincing LGM glacial sediment? With no recognition of clear ice-sheet marginal deposits prior to the Paviland Moraine being identified, the inland limit not surprisingly varied between publications and researchers (Fig. 29.12). A widely adopted post-Charlesworth (1929) limit was that provided by Bowen (1970), which showed a SE–NW alignment across the peninsula. Although not stated, the limit was probably guided by an earlier one based in part on the mineralogy of glacial sediment (Griffiths 1940), by obstructions to southward ice flow presented by Cefn Bryn, Ryer's Down and Llanmadoc Hill, by glaciogenic sediment at Whiteford Point, the capstone of Arthur's Stone on the northern slopes of Cefn Bryn regarded as a last-glaciation erratic (Owen 1964) and later dated using cosmogenic ^{36}Cl to 23.2 ± 0.2 ka (Bowen et al. 2002), and by proposed interglacial palaeosol remnants inland of Hunts Bay (Clayden 1977) and in a nearby coastal succession (Case 1993). Bowen's later ice limits showed similar across-Gower alignments but with variations in the west probably influenced by emerging evidence, including Paviland Moraine sediment (Smith et al. 2002), amino acid ratios (AARs) from fossil beach deposits (e.g. Bowen et al. 1985) and convincing evidence of LGM ice reaching north-west Gower (Campbell et al. 1982; Campbell and Shakesby 1994; Shakesby et al. 2000). For the BRITICE project, which used existing sources to map last glaciation sediments and landforms, Clark et al. (2004) drew their limit from Rotherslade to the north Gower shore at Crofty, presumably accepting the existence of a moraine remnant here. This limit, however, seems to be contradicted in the follow-up explanatory publication by Evans et al. (2005, p. 288) in which it is stated that there is 'firm stratigraphic evidence of Late Devensian ice on the west side of Gower... at Broughton Bay', which lies more than 10 km to the west.

Rijsdijk (2000) and Hiemstra et al. (2009) proposed that LGM ice forming a lobe in Swansea Bay in fact did not extend over the south-east corner of Gower to reach Rotherslade as most researchers following Charlesworth (1929) have accepted. They attributed the glaciogenic sediment in the succession there to proglacial, paraglacial and glaci-fluvial processes beyond the ice lobe, for which there is sea-floor bathymetric and sedimentary support (Culver and Bull 1980; Gibbard et al. 2017). The importance of this view reaches beyond the implied slight eastward adjustment required to the ice limit. It opens up the possibility of glaciogenic sediment in exposures west and east of Rotherslade being explained by a single set (proglacial) rather than different sets (periglacial to the west and periglacial, glacial and glaci-fluvial to the east) of processes. It thus addresses the first problem outlined above, but it then raises a new one of

requiring a precise ice margin configuration in order that proglacial processes could have contributed sediment to all the coastal dry valley fans (McCarroll and McCarroll 2015). In addressing this problem, Shakesby et al. (2018) point out that this new explanation applies well to those successions in south-east and in west Gower, where routes for proglacial sediment from ice front to dry valley fan can be easily reconstructed. Between Rotherslade and Threecliff Bay, however, fans containing glacial sediment are traceable not only to dry valleys but also to small cliff notches with tiny plateau-top catchments. If the Welsh Moor ridge is a recessional moraine, as already discussed, then it is possible to envisage an ice lobe extending S or SSE across central Gower to reach the coast and deliver sediment. At present, this is highly speculative, but this proglacial origin seems to offer a useful working hypothesis to explain the similar pattern and discrete glacial sedimentary units of dry valley successions along the south coast.

29.6 Coastal Landforms

29.6.1 Dunes

As sea level approached its present height in the mid-Holocene, sand is thought to have been eroded from glacial sediment on the sea-floor to form sand bars and dune-capped sand barriers close to the present shoreline (May 2003). Dune slack vegetation growing on the landward side

created peat deposits and, following continued sea level rise and coastline retreat up to the present day, they now crop out in subtidal zones seawards of the dune systems (or burrows, as they are locally known) on the western shore of Whiteford spit (Fig. 29.13) and in Swansea, Broughton and Oxwich bays. Archaeological evidence suggests that present-day Gower dunes reached more or less their present positions no earlier than the Bronze Age (c. 4500–2800 years ago in Britain) with some not established until the Iron Age (Lees 1982).

Historical and archaeological evidence (e.g. buried buildings and documentary sources) shows that many Gower dune systems, like those elsewhere in south Wales, extended in Medieval times (Potts 1968). The main cause appears to have been increasing frequency of severe storms (Pye and Blott 2010), although particularly high tidal levels may also have contributed (Toft 1988). Severe storms were reported from as early as 1188 and 1222 AD leading to sand blowing and flooding (Carr and Blackley 1980), but the main phase of activity was during the thirteenth–fifteenth centuries (Higgins 1933). At Pennard, documentary evidence is first provided in a report by William de Breos who allowed his huntsman, William de Hunde, and his family hunting rights on the ‘sandy wastes’ of his manor in 1317, and in 1478 tenement rents were lowered because of sand encroachment. By the 1520s, the church near Pennard Castle was finally abandoned, reportedly due to drifting sand. Nearby, remains of a suspected village (Stedwerlango), a substantial church and arable lands dating from the fourteenth century lie beneath Penmaen Burrows (Strahan 1907). According to

Fig. 29.13 Peat deposits on the foreshore on the western side of Whiteford spit exposed following a succession of strong storms in early 2014. (Photo Jessica M. Winder)



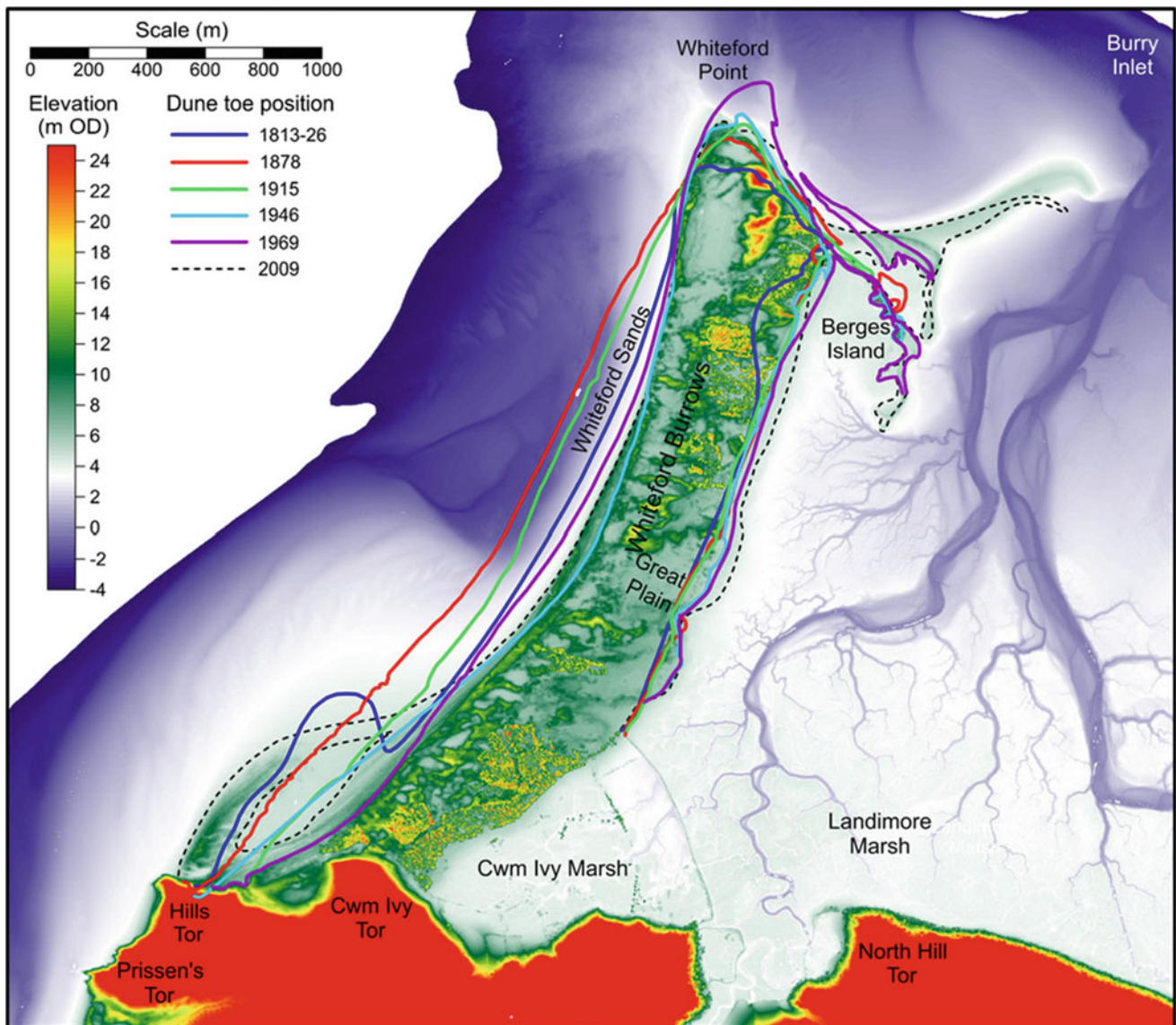


Fig. 29.14 Changes in the extent of Whiteford dune spit, 1813–2009. Reprinted by permission from Springer Netherlands. Reproduced from Robins NS., Pye K, Wallace H (2013) *J Coast Conserv* 17: 473. <https://doi.org/10.1007/s11852-013-0245-4>

Toft (1988), though, loss of interest in property maintenance rather than rapid sand inundation may have been the primary trigger for abandonment at one site at least. The sixteenth and seventeenth centuries also saw stormy conditions causing sand encroachment, but legislation by then led to powers to deal with the problem.

The most impressive dunes in Gower are the Hillend, Llangennith and Broughton Burrows (224 ha) and Whiteford (142 ha) systems. The latter comprises a c. 3-km long spit dune system resting at least partly on glacial sediment at the Loughor Estuary mouth. If glacial sediment does not underlie its whole length, the spit may actually represent a tombolo linking its southern end to such sediment seen at its

northern end. A W–E traverse across the spit shows fore, wandering, parabolic and mature dunes and blowouts aligned in the direction of the prevailing westerly winds (Potts 1968). About 50–100 m inland, the dunes reach some 16 m in height. The southern end of the spit has undergone accretion, erosion and renewed progradation since the 1980s, whilst most of the north-central part has witnessed net erosion. Longshore drift has produced a changing pattern of recurves at the northern tip (Robins et al. 2013; Fig. 29.14). Overall, there has been a loss of at least 5 ha since the 1890s (Rhind and Jones 2009). The Llangennith and Broughton dunes rest on a low limestone plateau and dune morphology is relatively chaotic, but a common form is

an elongated blowout, which Potts (1968) argued is a type of parabolic dune less well developed than those both at lower heights and nearer the beach.

Dune systems on the south coast are confined to bays (Port Eynon—Horton, Oxwich—Pobbles) with offshore-limited sand supplies (Rhind and Jones 2009). At Oxwich, the dunes are protected from the prevailing westerly winds by Oxwich Point and as a consequence, they show a clear ESE–WNW alignment, explained by ESE winds of sufficient strength (>15 kph) moving sand when dry conditions and low tides coincide (Harris 1974). Sediment budget calculations indicate the overall stability of this dune system (May 2003). In Nicholaston, Penmaen and Pennard Burrows, away from the sheltering influence of Oxwich Point, prevailing onshore south-westerly winds have carried sand up the limestone cliffs to a height of some 55 m, which can occur with wind speeds of 36 kph (Potts 1968).

Although the creation of and modifications to the Gower dunes have been emphasised, like dunes elsewhere in the UK and Europe those in Gower have become largely relict mainly because of loss of sand supply and inhibited mobility, nutrient enrichment and soil development (Rhind and Jones 2009). World War II training exercises caused intense disturbance of the vegetation and dunes in Broughton and Oxwich bays, but in post-war times trampling by visitors has been actively discouraged or prevented and, on Whiteford Burrows, Corsican pine plantations have contributed to dune stability. So far, post-war management policies have maintained a sub-climax or plagio-climax vegetation cover that has encouraged a state of geomorphological senility (Rhind and Jones 2009), but this management attitude looks set to be modified in the future.

29.6.2 Marsh

The relatively sheltered 45 km² Loughor Estuary provides suitable conditions for some 16 km² of salt marsh, most of which lies on the Gower shore. Here, Cwm Ivy, Landimore, Llanrhidian and Pen-clawdd marshes have a width of up to 1.5 km and stretch for some 13 km between Whiteford spit and Loughor. The marshes vary in height from c. 2.5 to 5.0 m above OD and have an almost imperceptible seaward slope. They are backed mostly by a line of vegetated hillslopes widely thought to represent fossil cliffs relating to high late Holocene sea level. The marshes are thought to rest on a variable thickness of glacial and glaci-fluvial sediment. Average annual flooding from the twice-daily tides varies between just four times at 4 m compared with 472 times at 3 m OD, these differences causing variations in sediment accretion, vegetation and morphology (Goodwin 1983). Landwards, silt and clay content, degree of decalcification, surface organic matter and soil ripening all increase. The

marshes are characterised by shore-parallel bands dominated by different vegetation assemblages. On the highest ground, where the marsh is flushed by freshwater, there is a *Juncus maritimus*-dominated assemblage, followed seawards by one with salt-tolerant grasses, then *Puccinellia maritima* followed on the sandflats at the seaward margin before 1935 by a dominance of *Salicornia*. In 1935, the hybrid marsh plant *Spartina anglica* was introduced east of Whiteford spit to promote sediment accretion and marsh growth. It effectively replaced *Salicornia* as the primary coloniser and also invaded the *Puccinellia maritima* zone. The effectiveness of the introduction is shown by the following: in the 110 years between 1790 and 1900, the north Gower marshes increased in area by some 307 ha, whereas in the following 60 years, which includes the introduction of *Spartina*, they had increased in area by a further 252 ha (Plummer 1960).

The very shallow marsh gradient is punctuated by small breaks of slope (or micro-cliffs) about 25 cm high, suggesting phases of deposition and erosion. More prominent features are the tidal creeks and salt pans. Landwards, the creeks become shallower but more permanent. Large sediment-laden tides overtopping creek banks deposit coarser sediment first, raising the banks slightly to form levées. Creek sides are affected by slumping following scour and possibly also frost action. Both blockage by these processes and the collapse of subsurface pipes can cause the development of sinuous pans (Goodwin 1983). More circular pans are more commonly higher on the marshes. They may form initially as sinuous pans, but bank collapse may lead to more circular shapes. Other possible mechanisms suggested include turf decay through burial beneath tidal debris, excessive waterlogging and dead mammals (sheep and ponies that graze on the marshes and even reportedly a dolphin) (Goodwin 1983).

In addition to introducing *Spartina anglica*, people have affected the marshes in other ways. The main estuary channel was observed to wander naturally between more southerly and northerly courses from the early eighteenth until late nineteenth century, but construction of a training wall in 1882 and its extension in 1918 partway across the channel to maintain navigation at ports on the northern shore promoted a northerly course. This encouraged marsh development along the southern shore, but between World War II and 1965, the wall was breached and not repaired causing the channel to adopt a more southerly course and encouraging renewed erosion of the north Gower marshes (Potts 1968). Sheltered on the east side of Whiteford spit lies the relatively small area of Cwm Ivy marsh embanked in 1638, but breached recently with no plans for repair of the bank.

The marsh behind the dunes in Oxwich Bay has been modified by human action. In 1770, a wall was built to exclude seawater from the marsh allowing a large, meandering freshwater lake to be established. An extensive drainage ditch system created some 80 ha of pasture for



Fig. 29.15 Pwlldu Bay. Vertical aerial view shows where former quarrying of limestone took place on the western cliff and the storm beach ridges (dashed lines). The ridges comprise quarry waste material

reworked by wave action. ©GoogleEarth. Inset photograph provides a ground view looking south-westwards along the largest ridge. (Photo R. A. Shakesby)

sheep and cattle. The sea wall and ditch system became neglected sometime before World War II and during that war, the vegetation along with the dunes was substantially disturbed by military training exercises. The dune system and marsh (now brackish) are now prized for their biodiversity, in part resulting from human action. Relatively small areas of former marshland on the western side of Swansea Bay have been destroyed through infilling and urban development.

29.6.3 Artificial Beach Modification: Pwlldu Bay

In addition to intended changes in the Loughor Estuary and on Oxwich Marsh already discussed, a once-thriving industry at Pwlldu Bay caused inadvertent modification. Between the late sixteenth and turn of the twentieth century, limestone was quarried from the cliffs bordering the bay and shipped to limekilns producing lime for agriculture in south-west England. Drilling and blasting of the cliffs took place all year. During summer, limestone blocks were loaded manually onto ships in the bay. Smaller cobbles and pebbles were avoided, apparently because they would have taken too long to load and unload (Jenkins 1977). They became

reworked by wave action to form the atypically large storm beach ridges that dominate the bay today (Fig. 29.15). The first ridge had already formed as early as 1808, just prior to the industry's heyday (Jenkins 1977).

29.7 Concluding Remarks

Gower has a richness of geomorphological phenomena that belies its small size. Most UK-based geomorphologists will be aware of, or have taken a close interest in, one or more of the peninsula's many landform and sediment attractions, which include spectacular coastal landforms and processes, enigmatic glacial and periglacial sediments and landforms, evidence for and impacts of Quaternary sea level change, relation of surface form to bedrock geology and long-term landscape development. In terms of understanding: (1) there has been a wide disparity in the amount of research effort given to the different topics; (2) even for the most intensively researched subject matter—Quaternary environmental changes and their effects—understanding remains far from complete and (3) given their significance, the formation and age of the planation surfaces, especially the widespread 60-m surface, warrant revisiting.

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Simon Carr

Abstract

The Brecon Beacons of central and southern Wales offer the opportunity to explore a range of geomorphological processes, particularly those relating to the rapid climate changes associated with the period subsequent to the Last Glacial Maximum. The mountains present some of the best preserved evidence in the British Isles of the interplay between glacial, periglacial and paraglacial processes, associated with conditions of marginal glaciation, and provide the most southerly evidence of Younger Dryas/Loch Lomond Stadial glaciation of Britain. The absence of evidence for landscape evolution in the region prior to the Last Glacial Maximum has recently begun to be addressed through insights derived from the subterranean geomorphology of limestone found in the south of the region. As one of the key sites of the early Industrial Revolution, the Brecon Beacons also preserve a unique landscape of anthropogenic (or even anthropocenic) geomorphology associated with large scale coal and iron extraction.

Keywords

Brecon Beacons • Sandstone • Limestone • Glaciation • Paraglacial • Periglacial • Anthropogenic landforms

30.1 Introduction

The Brecon Beacons are perhaps some of the most easily accessible mountains in the British Isles, and offer a dramatic landscape particularly when viewed from the Usk valley, described by Symonds (1872) as ‘waves poised to crash over the lowlands of Brecknock’. Located in south-central Wales

(Fig. 30.1), the Brecon Beacons was designated a National Park in 1954, with the western area of the park becoming a UNESCO Global Geopark (the Fforest Fawr Geopark) in 2005, based upon its rich geological and geomorphological heritage (Ramsay 2017). The entire region is known as the Brecon Beacons, but in the strict sense, this name only applies to the central spine of the highest mountains between Glyn Tarell and Talybont (Fig. 30.1).

The geomorphology of the Brecon Beacons is dominated by four distinct upland areas reaching a maximum elevation of 886 m but more typically elevations 600–650 m, forming a generally east-west trending escarpment, comprising mainly of Devonian Old Red Sandstone. The overall relief is typically 600 m between summit and the River Usk, but this moderate relief is amplified by the distinctive scarp of the mountains. The scarp faces northwards, and has been shaped into a series of dramatic glacial trough-heads with ~300 m of incision (Fig. 30.2a), with shallower valleys on the dip slope of the escarpment (Fig. 30.2b). The Black Mountains are the exception, where long south-easterly trending troughs demonstrate a structural control in the Old Red Sandstone as the escarpment bends toward the north-east. The River Usk cuts through the main escarpment, separating the eastern Black Mountains from the other three areas of upland (Brecon Beacons *sensu stricto*, Fforest Fawr and Black Mountain/Mynydd Du) to the west. Other than the Usk, most of the rivers drain from the watershed of the escarpment, with the northern rivers feeding into the Usk catchment, and the southward flowing rivers feeding the Tawe, Neath, Taff and Rhymeny basins (Fig. 30.1).

This region holds particular significance in the development of our understanding of Earth history since ~500 million years ago, with figures such as Adam Sedgewick and Roderick Murchison undertaking pioneering work in the Brecon Beacons to define the Ordovician, Silurian and Devonian periods, establishing key foundations for the modern geological time-scale. The landscape of the Brecon Beacons is also well-known for the historical development of the Glacial Theory in the British Isles, with the Rev.

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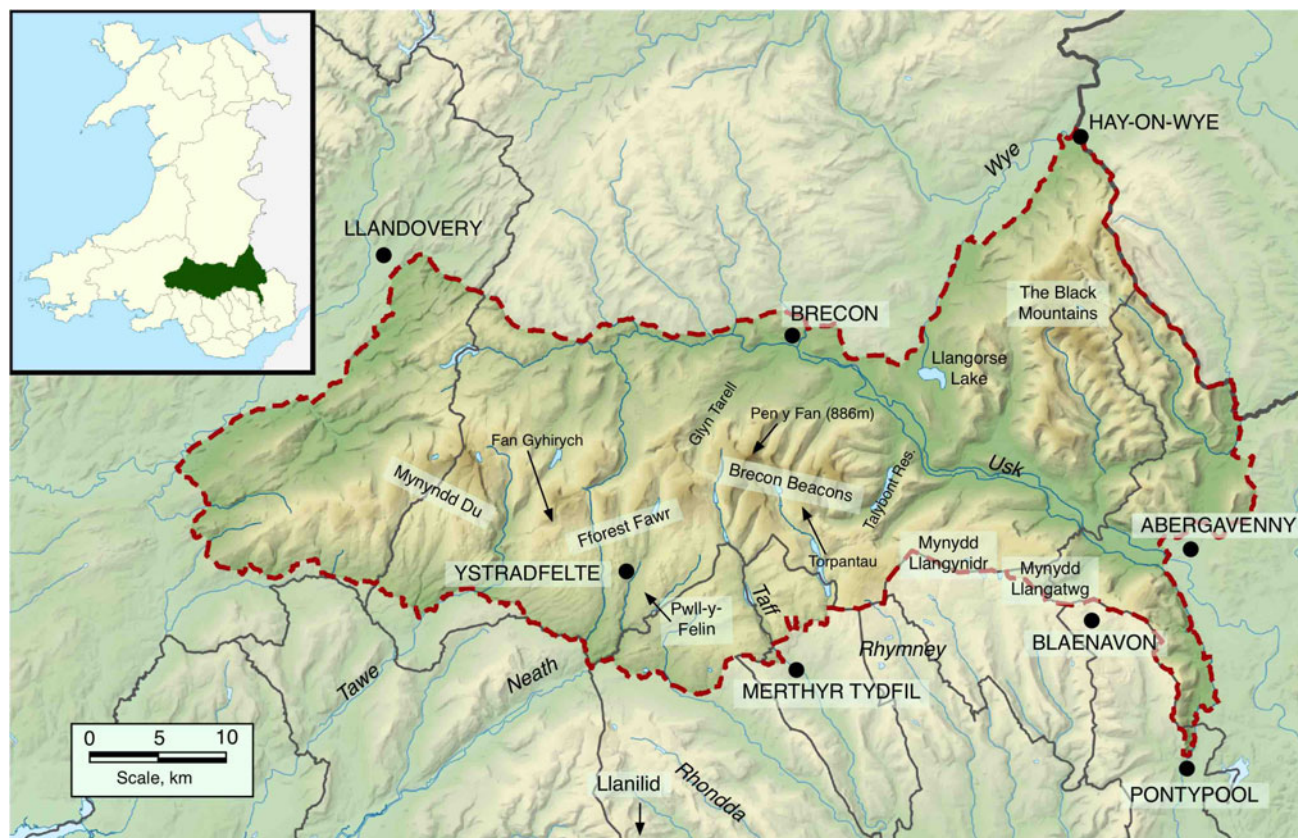


Fig. 30.1 Map of the Brecon Beacons. Boundary of the national park overlain on Digimap shaded relief model. Main settlements, mountain areas and river catchments are illustrated, as well as key sites mentioned

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William Symonds first suggesting in 1872 that the region had experienced past glaciation. Subsequently, Thomas Mellard Reade presented in 1894 the first detailed study of the moraines found at many trough-heads in the area, and which offer the most southerly evidence of glaciation in the British Isles during the Younger Dryas (Shakesby and Matthews 1993; Shakesby 2002; Bickerdike et al. 2018). Finally, along the southern boundaries of the National Park, the Brecon Beacons preserves classic landscapes associated with coal and iron extraction and processing marking the onset of the Industrial Revolution, and offers an historical insight into the developing Anthropocene geomorphology of the British Isles.

30.2 Geology

The bedrock geology of the Brecon Beacons comprises entirely of sedimentary rocks, and preserves an almost complete succession extending from the Late Ordovician through to the Carboniferous (Fig. 30.3), representing the infill of a deep ocean basin, at least two phases of mountain building, and a time-period associated with the emergence of

life on land (Howells 2007; Humpage 2007; Ramsay 2017). In general, the geology of the Brecon Beacons dips and youngs towards the south. From a historical perspective, the region has importance due to the Silurian period being named by Murchison in 1839 after the Celtic Silures tribe that occupied south-east Wales and Fforest Fawr and whom fiercely resisted the Roman invasion of Wales in around AD 48, and also the region is known as the type site of the lowest epoch of the Silurian System (the Llandovery Series; Cocks et al. 1984) just to the northwest of the Brecon Beacons.

The oldest Ordovician and Early Silurian sequences are located at the north-western flank of the Black Mountain, and fine-grained mudstones and siltstones represent deposition under deep marine conditions in the Rheic Ocean (Barclay et al. 2005). Subsequent uplift associated with the Caledonian Orogeny through the Mid- to Late Silurian and early Devonian results in a transition from progressively shallower marine and near shore-tidal environments, into the fluvial red-beds known as the (Lower) Old Red Sandstone (Barclay et al. 2005). These, at up to 1000 m thick, make up the bulk of the escarpment, and formed an alluvial plain with multiple fluvial styles extending from the Caledonian

Fig. 30.2 Physiography of the Brecon Beacons. **a** View of the north-facing escarpment, looking westwards toward Cribyn and Pen y Fan. Moraines associated with former mountain glaciation during the Last Glacial-Interglacial Transition are typically found below these steep scarps, where local microclimates permit (enhanced shading from solar isolation, adjacent plateau areas to contribute accumulation by snowblow). **b** More subdued topography on the south-facing dip slope of the Brecon Beacons, looking northwards to the summits of Corn Du and Pen y Fan. Extensive plateau surfaces with only moderate fluvial and glacial incision offer a significant contrast with the dramatic north-facing slopes (Photo Simon Carr)



Mountains to the north (Owen 1995, 2017; Wellman et al. 1998; Marriott and Hillier 2014; Kendall 2017). The extensive tabular sheets of the Lower Old Red Sandstone (St Maughans, Senni and Brownstone Formations) are magnificently exposed on the north-facing slopes of the Brecon

Beacons, Fforest Fawr and Black Mountain (Fig. 30.2). The Senni Formation preserves fossil traces of small, primitive vascular plants (Edwards and Richardson 2004; Ramsay 2017) as well as early aquatic vertebrates (jawless fish; Blieck and Elliott 2017). The Acadian Unconformity,

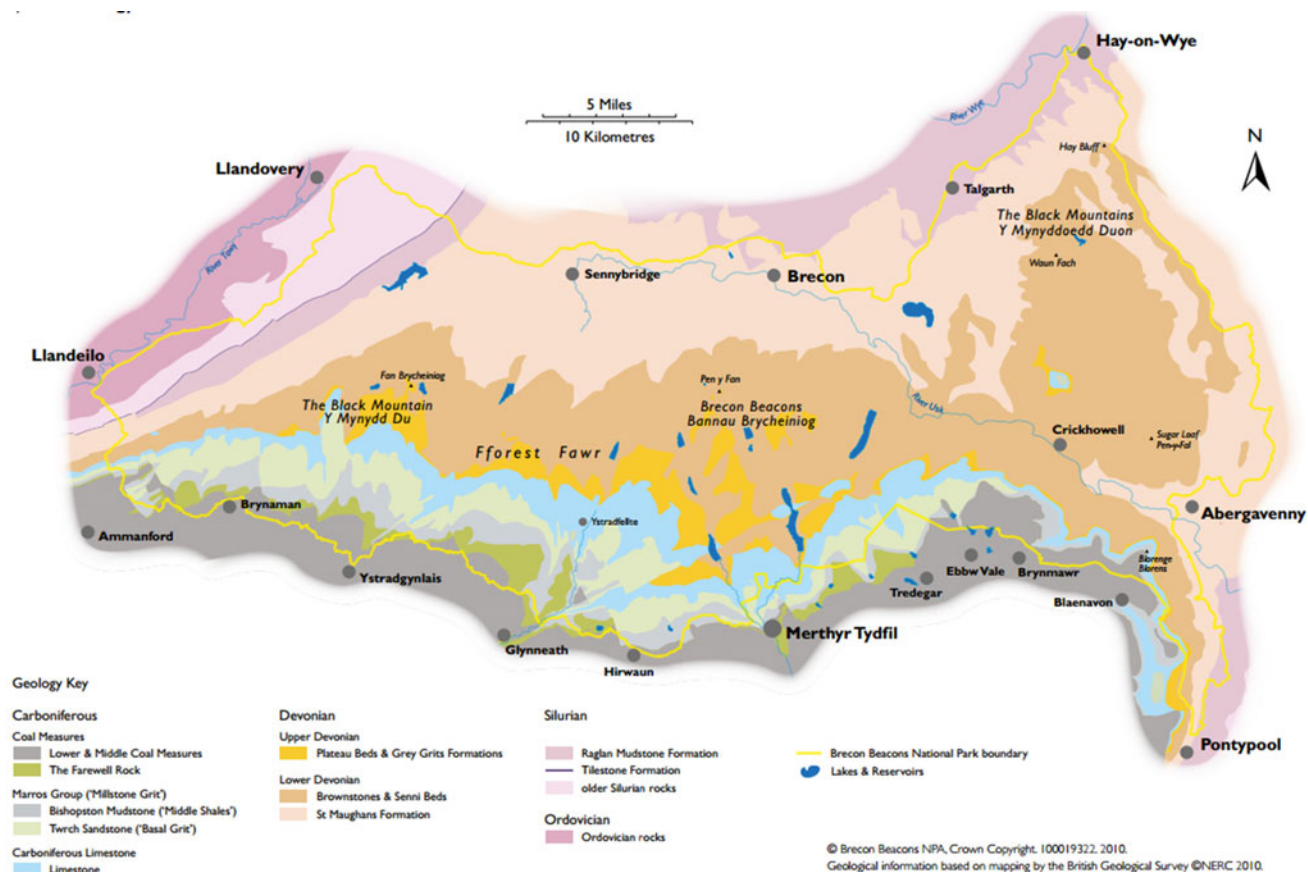


Fig. 30.3 Geological map of the Brecon Beacons (© Brecon Beacons NPA, Crown copyright 100019322. 2010). *Source* Brecon Beacons National Park [online]. Available at: <http://www.breconbeacons.org/geology>

considered to represent uplift at the culmination of the Caledonian Orogeny, truncates this lower sedimentary succession. Above this unconformity, the Upper Old Red Sandstone (Plateau Beds Formation, Grey Grits Formation) is found as pebbly conglomerates that form the distinctive summit caps of many of the mountains of the Brecon Beacons. These reflect deposition during the Late Devonian under a combination of aeolian, fluvial (braidplain) and tidal conditions associated with a major marine transgression related to significant regional subsidence (Barclay et al. 2005; Humpage 2007; Ramsay 2017).

During the Carboniferous, the Brecon Beacons were located on the southern margin of the Wales—Brabant High (Howells 2007; Ramsay 2017), and sedimentation of limestones and sandstones are associated with cycles of marine transgression and regression in a shallow tropical sea resulting in a thickening ramp of sedimentation on the southern flank of the Brecon Beacons. The Carboniferous limestones (Avon Group, Pembroke Group, both of Dinantian age) are characterized by siliciclastic mudrocks and thin beds of fossiliferous limestone, punctuated by thin palaeosols representing periodic marine regression (Humpage 2007;

Ramsay 2017). These cycles of sea level rise and fall are speculated to reflect eustatic sea level change associated with the growth and decay of a major southern polar ice sheet (Wright and Vanstone 2001). Unconformably overlying grits and sandstones characterize interbeds of marine, nearshore deltaic and fluvial sedimentation within the Namurian (Twrch Sandstone and Bishopstone Mudstone Formations) and offer further evidence of ongoing glacio-eustatic sea level change during the Carboniferous. Finally, in the south of the region, Westphalian coal measures (South Wales Coal Measures Group) are found, comprising mudrocks (including beds and nodules of sideritic ironstone), sandstones and interbeds of anthracite coal deposited in a fluvially dominated delta plain (Howells 2007; Humpage 2007; Ramsay 2017). From the late Carboniferous and into the Permian, the Brecon Beacons were significantly influenced by the tectonics of the Variscan Orogeny, which uplifted and imparted the southerly dips to the bedrock sequence seen today, and generated some low-grade metamorphism within the Coal Measures group to create spatial variation in the rank of coal present (Bevins et al. 1996). The uplift associated with Variscan Orogeny results in a regional erosional unconformity and stratigraphic

hiatus which persisted through until the Late Quaternary. Extensive swallow holes and sinks in the Carboniferous Limestone are attributed to Tertiary weathering (Humpage 2007), although these and other karst features seem to have also been actively formed through the Quaternary (Farrant et al. 2014).

There is a rich economic geology within the Brecon Beacons, that has had a substantial impact upon the geomorphology of the region, which can be considered one of the cradles of the Industrial Revolution. The co-location of both high-quality anthracite coal measures and iron ores means that South Wales became a major global centre for the production of iron and steel (Howells 2007; Ramsay 2017). Additionally, limestone quarrying and lime-burning, present in the region since the middle-ages, dramatically increased in the 19th and 20th Centuries to supply both the network of ironworks in South Wales and for agricultural purposes. The scale of modification of some of these landscapes, such as the Blaenau Valley is such that these represent some of the earliest examples of Anthropogenic landscapes, where human imprint dominates the valley geomorphology.

30.3 The Quaternary

The large-scale structure and geomorphology of the Brecon Beacons was probably established prior to the onset of the Quaternary Period, but it is also clear that the pre-Quaternary landscape has undergone significant modification during successive glacial-interglacial cycles (Lewis and Thomas 2005; Shakesby et al. 2007), particularly through glacial, periglacial and paraglacial processes. Fascinating insight into long-term landscape evolution in the region has emerged from the extensive Ogof Draenen cave system near Blaenavon (Simms and Farrant 2011; Farrant et al. 2014). The changing geometry and sediment infill of the cave systems have been interpreted as reflecting subglacial drainage conduits, probably active during the Anglian (MIS 12) glaciation, and Farrant et al. (2014) suggest that landscape modification in subsequent glaciations has been minimal. However, there is little direct surface evidence preserved for these events across Wales, with only inference of the glacial modification of pre-existing fluvial valleys (e.g. Sahlin et al. 2009), prior to the events associated with the Last Glacial Maximum (Late Devensian/Dimlington Stadial) and subsequent events (Fig. 30.4).

From the Late Quaternary, there is a wealth of geomorphological evidence in the Brecon Beacons of the maximum extent and retreat of the last (Late Devensian) British-Irish Ice Sheet, as well as subsequent events associated with the Last Glacial-Interglacial Transition (LGIT). Whilst traditionally regarded as a regional ice-dispersal centre during Quaternary glaciations, a re-interpretation of selected glacial

geomorphology by Jansson and Glasser (2008) suggests the region was more peripheral and marginal compared to the ice sheet scale glaciation that influenced much of Mid- and North Wales during the Devensian. This more restricted view of local glaciation has been strongly challenged by Shakesby and Matthews (2009), and is discussed in more detail below.

There is an extensive, high-resolution record of landscape and environmental change in the Brecon Beacons during the LGIT (Fig. 30.4), with the most southerly evidence in the British Isles for mountain glaciation during the Younger Dryas period (Carr 2001; Shakesby 2002; Carr et al. 2007, 2010; Bickerdike et al. 2016, 2018). In addition, long Lateglacial palaeoenvironmental records extracted from Traeth Mawr, Llanilid and Llangorse Lake (Walker 1982; Walker et al. 2003; Palmer et al. 2008) provide a detailed record of vegetation and climate change through this dynamic period of landscape evolution. The marginally glacial environments in the Brecon Beacons during the LGIT have resulted in a complex landscape whereby glacial, periglacial and paraglacial geomorphology is spatially and temporally closely associated, leading to uncertainty and ambiguity in their interpretation and palaeoenvironmental implications (Shakesby 2002; Shakesby and Matthews 2007; Carr et al. 2007; Coleman and Carr 2008). This results in a fascinating and complex record of landform and landscape evolution that is challenging to interpret.

30.4 Glacial Geomorphology

The main Brecon Beacons mountain belt would likely have acted as an ice accumulation and dispersal centre during multiple Quaternary glaciations, inferred by the spectacular northern face of the mountains, deeply sculpted by glacier erosion into the dramatic trough heads described by Symonds (1872). The southern slope of the mountains is less deeply eroded (Fig. 30.2b) and suggests that the geological structure of the Brecon Beacons over-emphasise the actual volume of Quaternary glacial erosion, and that much of the Brecon Beacons preserves a largely fluvial landscape (see for example Jansson and Glasser 2008). However, over-deepening of the upper reaches of the north-facing trough heads (Shakesby and Matthews 2009), and the breaches that divide the four main massifs of the Brecon Beacons are testament to active ice sheet glaciation and the migration of regional ice-divide across the mountain belt resulting in the formation of transection glaciers throughout multiple Quaternary glaciations (Shakesby et al. 2007).

During the Last Glaciation (Late Devensian), it would appear that the Brecon Beacons were peripheral to the overall British-Irish ice sheet (Lewis and Thomas 2005; Jansson and Glasser 2008; Evans 2016), and that compared

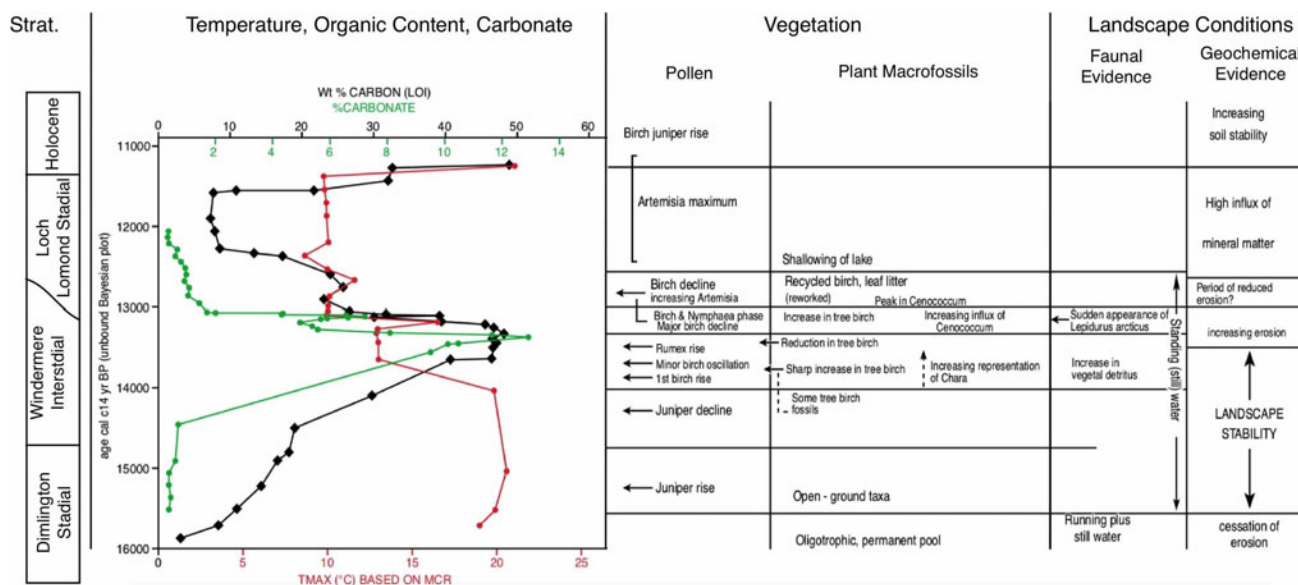


Fig. 30.4 Synthesis of the palaeoenvironmental record from Llanilid (adapted from Walker et al. 2003), showing the dramatic temperature shifts (derived from *coleoptera* mutual climatic range data), vegetation

and ecology of South Wales and the Brecon Beacons associated with the Last Glacial-Interglacial Transition

with ice-centres in Mid- and North Wales, the Brecon Beacons contributed relatively little to the volume of the Welsh ice cap during this period (Patton et al. 2013). Controversially, Jansson and Glasser (2008) propose that some of the erosional and depositional features identified in the trough heads of the central and western Brecon Beacons represent features generated by ice extending southwards from mid-Wales flowing up-valley into and over the escarpment of the Brecon Beacons during the Last Glaciation, rather than moraines and associated landforms of restricted glaciation during the Younger Dryas (Fig. 30.5). This view has been strongly critiqued by Shakesby and Matthews (2009), noting the selective use of previously published geomorphological, sedimentary and chronological evidence by Jansson and Glasser (2008) in arriving at their interpretations, and Shakesby and Matthews (2009) assert that the absence of mid-Wales erratics south of Trecastle and Llangorse indicates that locally-sourced ice from the Brecon Beacons deflected mid-Wales ice largely out of the Usk Valley (Fig. 30.5). The actual form of the most recent ice-sheet scale glaciation has not yet been adequately reconstructed, but it is likely that local plateau icefields on the main escarpment of the Brecon Beacons fed a series of outlet glaciers flowing down the main valleys, rather than there being a single large ice dome over the entire region, and some of the higher mountains are likely to have remained ice-free throughout the LGM (Lewis and Thomas 2005; Patton et al. 2013).

On the northern side of the Brecon Beacons escarpment, the LGM Usk Glacier drained the majority of the ice-dispersal

centre, forming a significant, highly active and erosive outlet glacier extending eastwards beyond Abergavenny (Coleman 2007; Thomas and Humpage 2007). Shorter and less erosive outlet glaciers drained to the south of the escarpment along the Taff, Tawe and Neath valley systems, with additional ice source areas evidenced by lower-altitude cirques and glacial trough-heads within the South Wales coalfield, particularly the Rhondda valley, contributing to the South Wales End Moraine complex (Bowen 1973; Lewis and Thomas 2005). The main outlet glacier of the region, the Usk Glacier, terminated in a piedmont glacier lobe forming a kame-moraine complex extending beyond the mountain front from Pontypool in the south across to Raglan in the east, becoming confluent with the Wye Glacier in the north, an outlet glacier draining central Mid-Wales (Humpage 1992; Thomas 1997; Lewis and Thomas 2005; Thomas and Humpage 2007). Thomas and Humpage (2007), Coleman (2007) and Coleman and Carr (2007) identify a suite of moraines, kame deposits and associated outwash sediments and landforms that record the progressive retreat, punctuated by occasional re-advances through the middle- and upper Usk valley (Fig. 30.6), and Coleman (2007) highlights the importance of the disconnection of small peripheral icefields, such as that on the Llangattwg plateau, in controlling the rate and dynamics of the retreat of the Usk Glacier. At Llangorse Lake, the contribution of ice from both the Wye and Usk Glaciers is recorded in a high-resolution lake sediment record (Palmer et al. 2008), which although currently floating in terms of geochronology, has yielded a detailed annually-resolved picture of the retreat and dynamics of these glaciers during deglaciation.

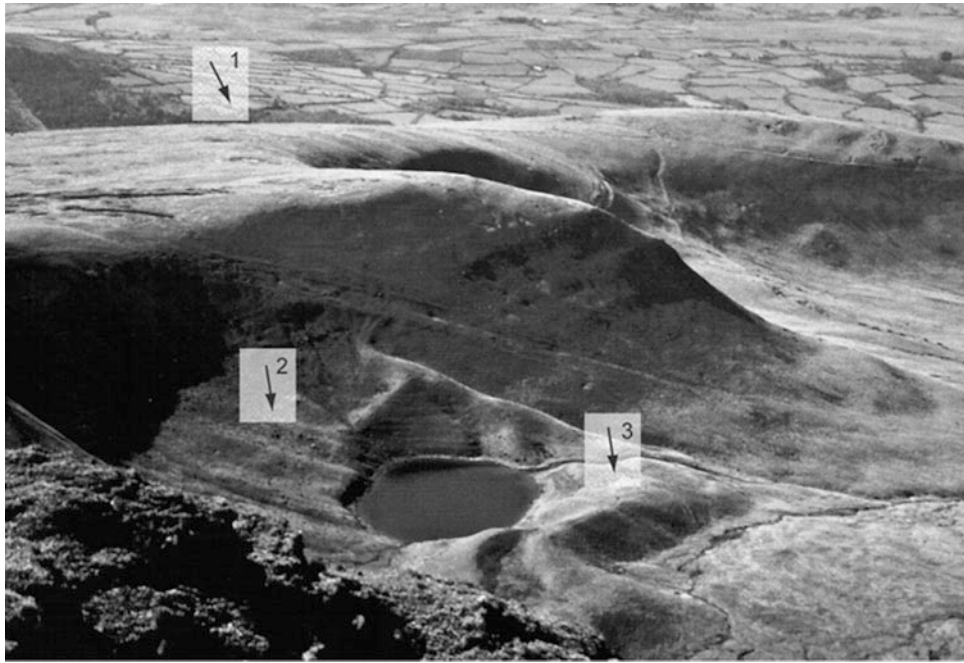


Fig. 30.5 Photograph of valley head and moraine at Cwm Llwh (photograph by CA Lewis), suggested to illustrate flow of mid-Wales ice southwards, up the valley, overtopping the Brecon Beacons. Number 1 indicates the plateau surface of the Brecon Beacons, Number 2 shows features interpreted by Jansson and Glasser (2008) as glacial lineations and Feature 3 is inferred to have been a moraine formed

during ice flow into valley head. This interpretation is robustly rejected by Shakesby and Matthews (2009), who demonstrate that features 2 and 3 represent Younger Dryas/Loch Lomond Stadial mountain glaciation. The lake is approximately 100 m across (image from Jansson and Glasser 2008)

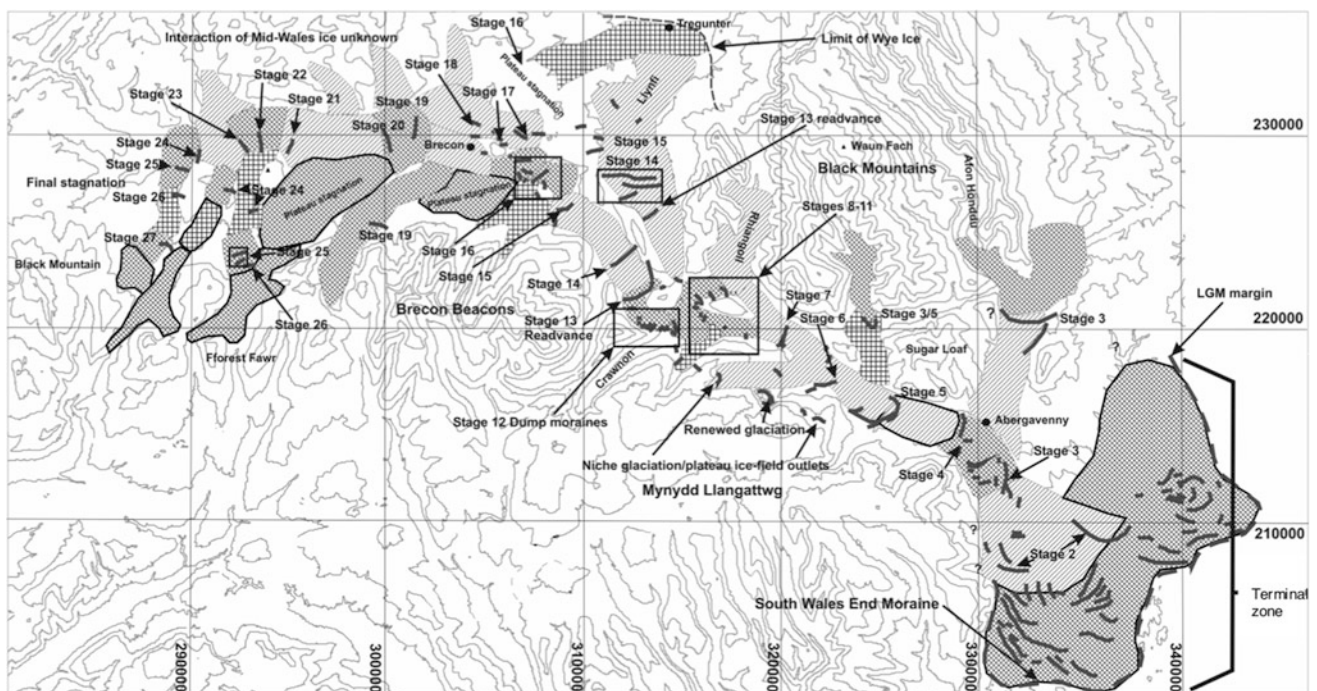


Fig. 30.6 Retreat stages and changing glacialfluvial landsystem for the deglaciation of the Usk Valley subsequent to the LGM (Coleman 2007). A total of 28 stages of ice retreat and readvance are identified from sedimentological and geomorphological evidence. Bold black lines

mark moraines. Active glacier retreat is marked by diagonal lines (pale shading), and rapid wastage or stagnation is marked by cross-hatches (darker shading)

During the LGIT, a short-lived reversion to extreme cold conditions during the Younger Dryas Stadial led to re-occupation of the high mountain trough-heads of all four sections of the Brecon Beacons by small mountain glaciers (Ellis-Gruffydd 1977; Carr 2001; Shakesby 2002; Coleman and Carr 2008). It is widely recognised that small lateral and terminal moraine ridges, typically lying at around 500–600 m elevations (Fig. 30.7) represent the most southerly evidence of Younger Dryas glaciation in the British Isles. The extremely marginal conditions for glaciation during this period have led to much discussion over the potential range of glacial and

non-glacial origins of these scarp-foot ridges in the Brecon Beacons, with particular focus on sites where the glaciation level was much lower, such as the features in the head of Glyn Tarell (Shakesby and Matthews 1996, 2007; Shakesby 2002; Carr et al. 2007). In these instances, a combination of geomorphology, sedimentology, glacier reconstruction and local climate modelling highlights the role of local topoclimatic influences (for example shading or the influence of snowblow from adjacent plateaux) in conditioning whether a valley head experienced glaciation or other cold-climate processes during the LGIT (Coleman et al. 2009).

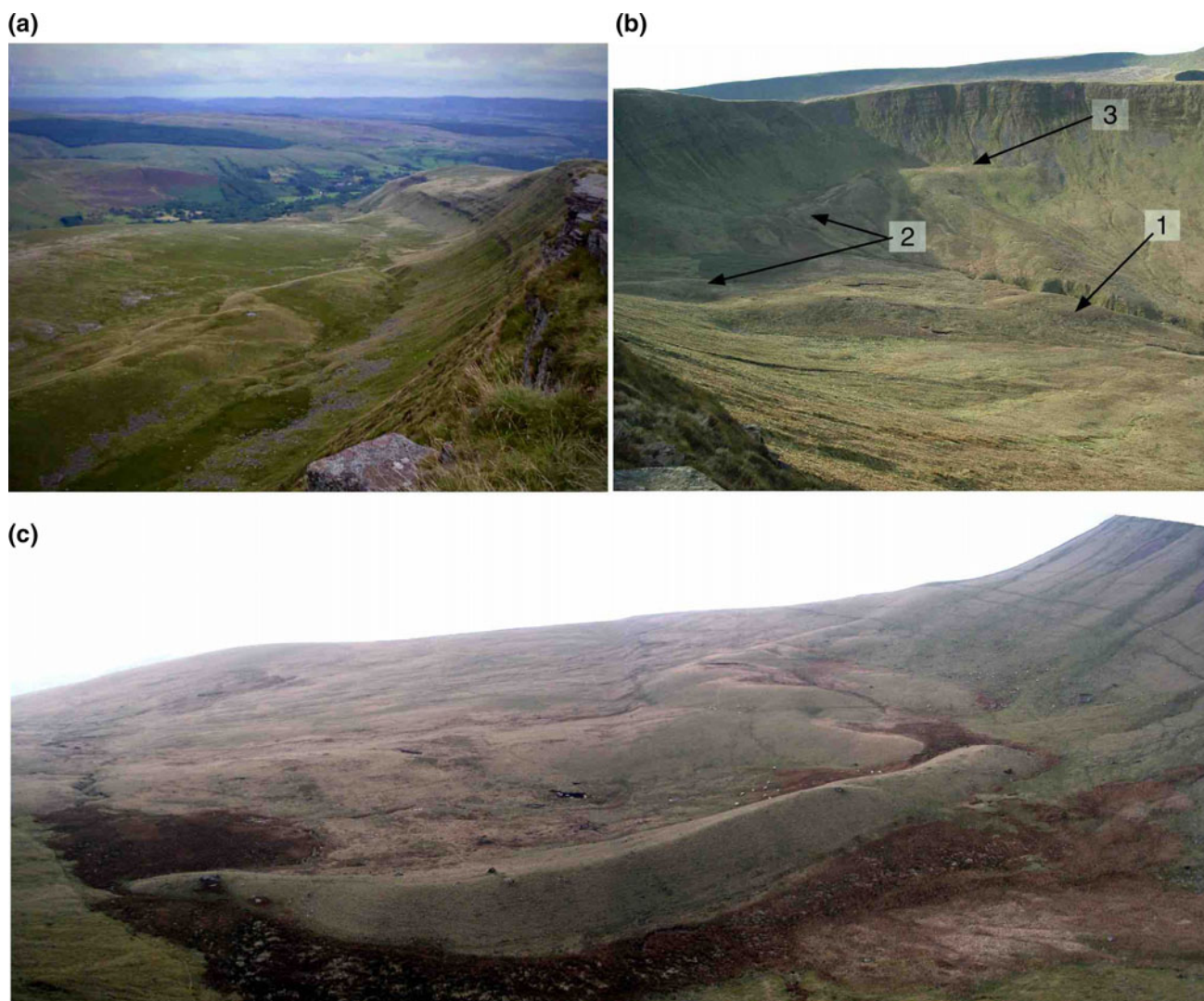


Fig. 30.7 Upland geomorphology associated with the Last Glacial-Interglacial Transition. **a** Long ridge running north-south beneath Fan Hir. This feature continues to be of interest, having been interpreted as a pronival rampart or terminal moraine of Younger Dryas age and even as a lateral moraine emplaced during the LGM. The consensus is that this feature is a Younger Dryas terminal moraine. **b** Series of ridges within Cwm Oergwm interpreted by Coleman and

Carr (2008) as terminal moraines associated with the maximum (1) retreat phases (2) of a Younger Dryas glacier, and a contemporaneous pronival rampart (3). **c** Complex of ridges within Cwm Sychlwch, beneath Fan Foel, Mynydd Du. Note also the well-developed talus accumulations described by Curry and Morris (2004) (Photo Simon Carr)

30.5 Periglacial and Paraglacial Geomorphology

As noted above, the marginal nature of glaciation of the Brecon Beacons during the LGM and through the LGIT has resulted in a suite of landforms in both the uplands and lowlands that reflect a diverse range of glacial, periglacial (cold climate, but non-glacial) and paraglacial (non-glacial processes conditioned by destabilisation of landscapes by glaciation) environments, such, that particularly for the uplands, it has often proven challenging to adequately interpret the geomorphological record.

Some of the upland scarp-foot ridge features in the Brecon Beacons have been interpreted by different authors as both moraines reflecting highly localised glaciation and as pronival ramparts associated with perennial snowbank formation under periglacial conditions during the Younger Dryas. A classic example of this confusion is demonstrated by the ridge at Fan Hir (Fig. 30.7a), which has been interpreted as a Younger Dryas terminal moraine (Shakesby and Matthews 1993), an LGM lateral moraine (Jansson and Glasser 2008) and a pronival rampart (Ellis-Gruffydd 1977). This reflects the challenge of interpreting the geomorphology of such marginal glacial and periglacial environments, and highlights the importance of collecting sedimentological data as well as using climate and physical modelling approaches to inform geomorphological interpretations. The value of this integrated approach is demonstrated by Coleman and Carr (2008) who interpret the various scarp-foot ridges within the neighbouring

trough heads of Cwm Oergwm (Fig. 30.7b) and Cwm Cwareli as a palimpsest of pre-Younger Dryas and Younger Dryas terminal moraines, a later perennial snowbank, and a subsequent small paraglacial rock-slope failure, through a combination of geomorphological methods. However, sites such as the nine scarp-foot features identified beneath the Mynydd Du ridge (Fig. 30.7c) continue to be enigmatic and may represent hybrid periglacial and glacial features dating from the LGIT. Beyond these scarp-foot ridges, the widespread presence of gelifluction lobes and terraces on the uplands of the Brecon Beacons, particularly well-preserved on Torpantau and near Fan Gyhirych (locations in Fig. 30.1) is evidence of periglacial activity, assumed to be of Younger Dryas age (Lewis and Thomas 2005), although the absence of pingo ramparts and ice wedge casts is suggested to reflect marginal periglacial, rather than permafrost conditions.

During the LGIT, the influence of glaciation as a mechanism of destabilisation of slopes is frequently preserved as large scale mass-movements in the Brecon Beacons (Fig. 30.8), and in particular there is a rich geomorphological record of paraglacial slope modification (Shakesby and Matthews 1996; Shakesby 2002; Curry and Morris 2004; Coleman and Carr 2008). In some cases, such as below the scarp of Craig Cerrig-Gleisiad in Glyn Tarell, it is possible to construct a morphostratigraphic sequence of deglaciation, paraglacial landslide development and subsequent modification of the landslide debris by a Younger Dryas glacier (Shakesby and Matthews 1996). However, at the majority of locations where rock-slope failures and other paraglacial

Fig. 30.8 Un-named and previously unreported rock slope failure beneath the Waun Rydd plateau, central Brecon Beacons. Image taken looking northeast from Craig y Fan Ddu. It is evident that large-scale paraglacial mass-movements are common in the region, albeit not commonly reported (Photo Simon Carr)



slope modifications have been identified (Fig. 30.8), it has proven difficult to establish whether these relate to landscape instability during the LGIT or within the early Holocene. However, detailed work on the talus accumulations along the escarpment of Mynydd Du (Curry and Morris 2004; see Fig. 30.7c) suggests that rapid rock-wall retreat during the LGIT was associated with highly effective diurnal-style freeze thaw weathering of unstable, paraglacial rock slopes resulting in rockwall retreat rates some two orders of magnitude greater than present-day levels.

30.6 Fluvial Geomorphology

As noted earlier, whilst the northern escarpment of the Brecon Beacons is striking, with clearly glacially-modified trough heads, the overall landscape of the mountains is predominantly one of moderate relief, and it has been suggested (albeit controversially) that the overall form and geometry of the Brecon Beacons is fluvial in origin (Jansson and Glasser 2008; Sahlin et al. 2009; Shakesby and Matthews 2009). As such, the valley systems of the Brecon Beacons may imply a persistent landscape preserved throughout multiple Quaternary glaciations. However, even if this is the case, there is little direct geomorphological evidence of sediments or landforms of fluvial origin prior to the Holocene.

There has been little formal geomorphological research published on the modern fluvial catchments associated with the Brecon Beacons. The dominant modern river catchment of the Brecon Beacons is that of the Usk, which at ~120 km in length, and a catchment of 1358 km² is one of the largest in Wales (Larsen et al. 2009). The catchment experiences modest baseflow (~15% of discharge), and consequently discharge and sediment load is subject to significant fluctuations associated with stormflow (Environment Agency 1998). For much of its course within the Brecon Beacons, the River Usk is a single-thread bedrock river channel, which has also eroded into the Quaternary glacial landscapes, with modest floodplain development in the middle reaches. Once beyond the mountain front at Abergavenny, the Lower Usk extends across a large alluvial floodplain, with a complex suite of migrating meander loops, cut-off and backwater features.

Where the underlying bedrock geology comprises Carboniferous Limestone, mainly in the south and east of the Brecon Beacons, particularly the upper reaches of the Tawe and Neath catchments, the hydrology and fluvial behaviour of catchments is strongly affected by karst processes.

30.7 Karst Geomorphology

The presence of Carboniferous Limestone results in some surface karst geomorphology and much more extensive sub-surface karst cave systems within the Brecon Beacons. The limited surface exposure of limestone in a narrow band extending across the southern part of the Brecon Beacons restricts the exposure of classic limestone pavements, which only cover approximately 20 ha in total, comprising numerous isolated patches, many of which have been degraded by quarrying and removal of limestone blocks for building stone (Fig. 30.9). Dolines can be found throughout the limestone belt of the Brecon Beacons, some of which are ephemerally flooded, such as the feature at Pwll-y-Felin (Farr et al. 2016), or the numerous examples on the Mynydd Llangynidr (Gunn 2012) which demonstrate different behaviour including both water retention or acting as stream sinks to subsurface karst. These dolines thus reflect complex hydrological behaviour reflecting the balance of input of surface water and subterranean conduits associated with the structure of the Carboniferous Limestone, particularly the role of small scale localised variations in water solubility associated with the presence of interstratal karst (Farr et al. 2016).

However, the subsurface karst geomorphology of the Brecon Beacons is much more extensive and dramatic, with some of the longest surveyed cavern systems in the world, including over 70 km of passages in the Ogof Draenen and Mynydd Llangatwg cave systems near Blaenavon (Simms and Farrant 2011) as well as the well-known tourist show-caves at Porth yr Ogof and Dan yr Ogof near Ystradfellte. Perhaps the most striking example of sub-surface karst geomorphology is the cavern system at Ogof Draenen, which comprises four linked, vertically-stacked, but genetically separate cave systems (Farrant et al. 2014), of which only the lowest is currently hydrologically active. Cave survey, sediment analysis and U-series dating of speleothem is utilised by Farrant et al. (2014) to infer a complex series of surface topography and drainage changes over the past ca. 0.5 Ma. In particular, massive influxes of sediment, sufficient to choke the upper passages of Ogof Draenen, are interpreted as flushes of glacialfluvial sediments emplaced during the Anglian (MIS 12) glaciation, when the cave systems acted as subglacial meltwater 'underspill' systems. Critically, Farrant et al. (2014) infer substantial changes to the surface topography occurred in the Brecon Beacons during this early glaciation, and that glaciations subsequent to the Anglian have done little to further change the overall relief and regional scale geomorphology of the Brecon Beacons.

Fig. 30.9 Fragment of limestone pavement, Garwnant Fawr, Taff Valley. Image taken looking north. To the southwest of this pavement, dolines and sink-holes are common to the summit of Cadair Fawr (Photo Simon Carr)



The findings of the research in the Ogof Draenen demonstrate the importance of sub-surface geomorphology as a key form of evidence to inform the development of reconstructions of long term landscape evolution, particularly where human impact on the landscape may have substantially altered surface geomorphology.

30.8 Anthropogenic Geomorphology

The geomorphology of the Brecon Beacons, as with most other areas of the British Isles, is a palimpsest landscape of shared natural and cultural elements associated with persistent human occupation and modification of the pre-existing, post-glacial environment. The climatic amelioration at the end of the LGIT is associated with the first arrival of Mesolithic hunter-gatherers into the Brecon Beacons, from whom the clearance of the wooded landscape of the region by fire provides the first cultural imprint on the landscape (Leighton 2012; Ramsay 2017). The impact of these, and subsequent waves of agricultural settlers in the early Neolithic through to the Iron Age, is recorded in the substantial decline in woodland cover, replaced by upland heather moorland and blanket bogs, permanently changing the vegetation, ecology and hydrology of the region (Leighton 2012). Expansion of agriculture, particularly of sheep grazing since the Medieval period, has seen a further transition from heather moorland to acid grassland. The indirect

geomorphological legacy of pre-industrial human occupation of the Brecon Beacons is thus considerable and pervasive, in terms of accelerating erosion and sedimentation, particularly of soils, and changing the significance of chemical weathering through acidification. This perhaps marks the start of a transition towards an anthropocenic landscape whereby geomorphological processes are dominated by human agency.

The onset of extensive production of iron in South Wales during the mid-18th Century, utilising the rich iron and coal reserves located in the southern part of the Brecon Beacons (Morgan 2005; Ramsay 2017) represents some of the earliest global evidence of the Industrial Revolution. The direct anthropogeomorphological signature of large scale mining, particularly associated with the deposition of mining spoil tips, is considerable in the vicinity of Blaenavon, such that Haigh (1979) suggests the landscape is dominated by artificial landforms. The anthropogeomorphology of these spoil tips (Fig. 30.10) reflects the evolution of different processes of sediment transport, from flat-topped fan and plateau tips resulting from use of rail wagons to move spoil, through to more recent ridge and conical tips deposited by aerial bucketways and conveyor belt systems. Whilst the large-scale extraction of coal and iron in South Wales has largely ended, the geomorphological legacy of such modification of the landscape is still recorded in monitoring of soil and water quality, erodibility and localised sediment transport (Haigh 1980, 2000).

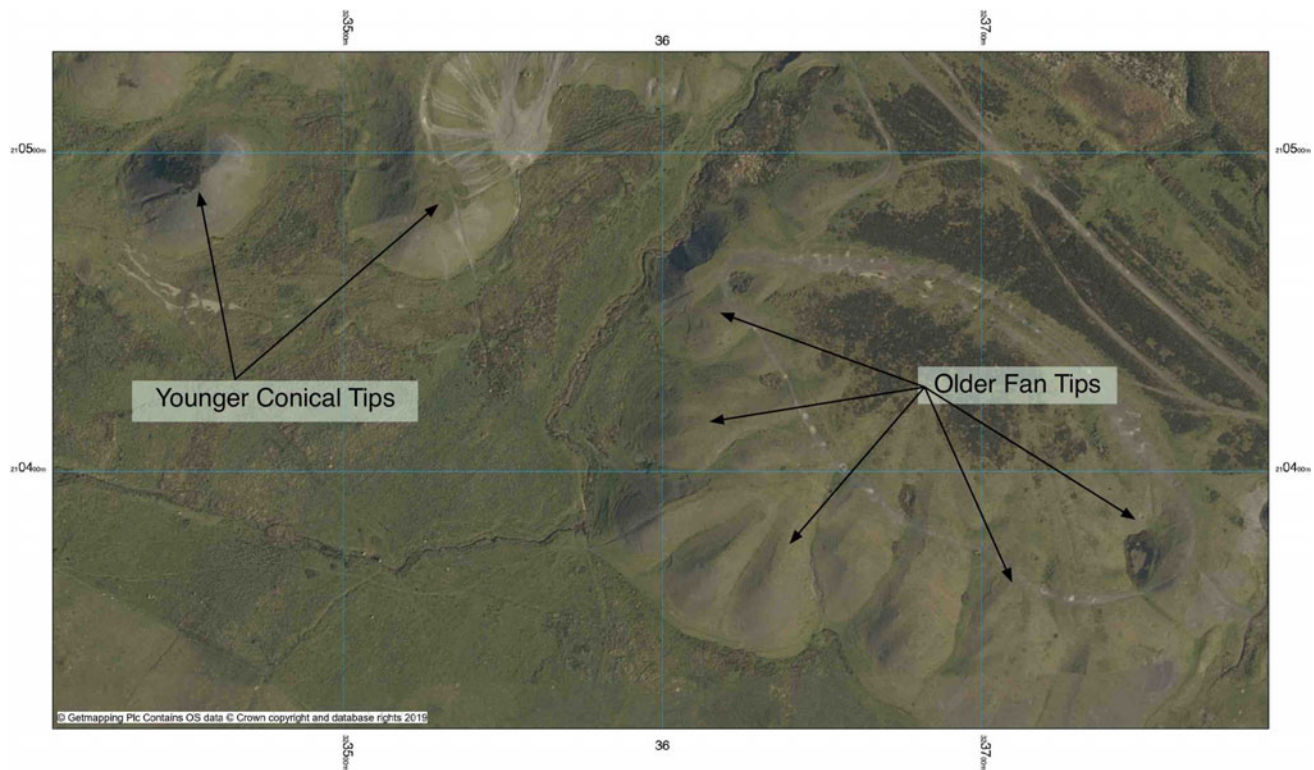


Fig. 30.10 Aerial photo of fan-type and conical spoil tips at Garn-yr-erw, northwest of Blaenavon. The entire landscape of the upper Blaenau valley and those surrounding it are dominated by such artificial landforms, relating to the extraction of coal and iron in the

valleys extending south of the Brecon Beacons Aerial imagery © Getmapping Plc, with Ordnance Survey grid © Crown copyright and database right

30.9 Conclusions

The Brecon Beacons, defined by the boundary of the Brecon Beacons National Park, is dominated by the mainly Devonian Old Red Sandstone escarpment, which is itself part of a regional sequence that Sedgewick and Murchison used to define and establish Earth's history over the past ~500 million years. The main escarpment, split into four main upland areas, offers a wealth of glacial, periglacial and paraglacial evidence of the geomorphological impact of Late Quaternary environmental change, and offers the most southerly evidence of glaciation of the British Isles during the Younger Dryas. Whilst there is ongoing tension between researchers with regard the significance of Quaternary glaciation in shaping the surface landscape of the Brecon Beacons, it is perhaps the hidden record of subterranean karst in the south of the region that is yielding the most exciting and tantalising information about the long-term landscape evolution of the region. Whilst post-glacial landscape development in the Brecon Beacons has perhaps been less dramatic, the pervasive impact of humans as a geomorphological agent is particularly well represented in the

region since pre-historic times, with localities such as Blaenavon illustrating the significance, or even the dominance of humans over the physical landscape.

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