CONSTRAINING THE ALTITUDINAL RANGE OF SUB-HORIZONTAL DENUDATION SURFACES IN WALES, U.K., USING THE ELEVATION-RELIEF RATIO

Dr. Matt D Rowberry
School of Geosciences, University of the Witwatersrand, Private Bag 3, 2050 Wits, South Africa
mathew.rowberry@wits.ac.za

ABSTRACT

This paper uses the elevation-relief ratio to constrain the horizontal and vertical extent of sub-horizontal denudation surfaces in Wales, United Kingdom. The elevation-relief ratio has been chosen as the appropriate geomorphological parameter as it allows such surfaces to be mapped analytically, even in areas that have been subjected to considerable linear denudation; thus, the technique is applicable in a wide range of topographic settings. For the first time, the elevation-relief ratio has been calculated through the interrogation of the SRTM DEM, using ESRI ArcMap 9.2 GIS software; the methodology has been described in detail. Five sub-horizontal denudation surfaces are recognized at between 40-90 m asl, 118-132 m asl, 173-187 m asl, 219-229 m asl, and 385-520 m asl. The number and altitudinal range of these surfaces has not been recognized in any previous study; the enduring tripartite division of the Welsh landscape envisaged by Brown (1960) must now be rejected, both in terms of the number of surfaces that may be recognized and their altitudinal range.

Key words: sub-horizontal denudation surfaces, elevation-relief ratio, SRTM data, ESRI ArcMap, Wales.

1. INTRODUCTION

Over the past twenty years there has been a considerable increase in the volume of geomorphological and geophysical research that has focused upon landscape evolution over geological time-scales (*cf*. Summerfield 2005; Bishop 2007). This upsurge has frequently been stimulated by the advent of high-resolution global digital elevation models (DEMs), which have enabled enduring physical models of landscape evolution (*e.g.* Davis 1899, 1902; King 1951, 1953, 1976) to be tested with considerably greater scientific rigour than has been possible previously (Bishop 2007). Many such studies are underpinned by the identification and correlation of sub-horizontal denudation surfaces, despite numerous controversies surrounding this field of research (*e.g.* Chorley 1965a, 1965b; Summerfield 2005); such controversies are particularly contentious where these surfaces have been uplifted, as any uplift will lead to widespread incision which serves to destroy the initial surface. Despite these difficulties, the geomorphological mapping of such surfaces continues to underpin recent studies from, for example, the passive continental margin of northwest Europe (*e.g.* Bonow *et al*. 2003; Fjellanger & Etzelmüller 2003; Olvmo *et al*. 2005; Rowberry *et al*. 2007). This paper builds upon that theme by using the 3 arc-second NASA Satellite Radar Topographic Mission (SRTM) DEM in order to elucidate the horizontal and vertical extent of sub-horizontal denudation surfaces within Wales, United Kingdom (Figure 1). Critically, this study represents a pioneering attempt to map such surfaces through the application of the elevation-relief ratio (Wood & Snell 1960); it is more customary for such studies to use the standard geomorphological parameters of slope angle or relative relief. The elevation-relief ratio is an important, if underutilized, geomorphological parameter as it allows such mapping to be undertaken through the application of an entirely analytical methodology.

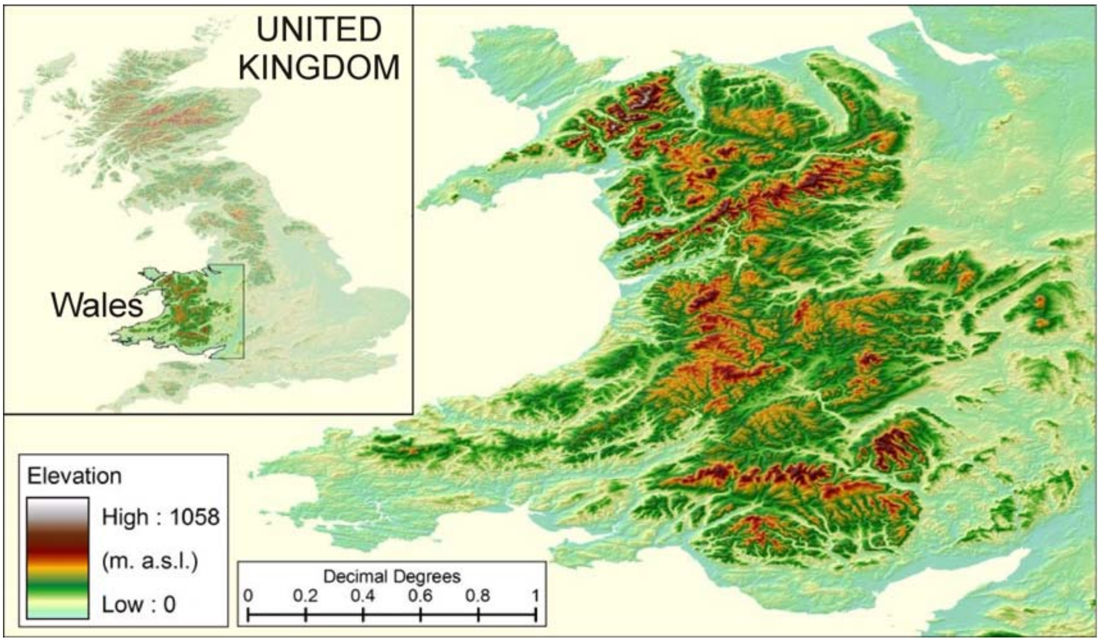

Figure 1 -Location (inset) and topographic maps of Wales, United Kingdom; the DEM was constructed from the SRTM dataset, which has a horizontal resolution of 3 arc-seconds.

2. AIM AND OBJECTIVES OF THE PRESENT PAPER

The overall aim of the present paper is to demonstrate the value of the elevation-relief ratio as a geomorphological tool, which is able to analytically identify sub-horizontal denudation surfaces within heavily dissected landscapes; therefore, the elevation-relief ratio may be applied in a diverse range of geological and tectonic settings beyond the passive continental margin of northwest Europe. In order to achieve this aim, a number of research objectives must be addressed. First, it is important to adequately detail the methodology required to calculate the elevation-relief ratio within a geographical information systems (GIS) framework. Second, it is important to consider the manner with which the calculated elevation-relief ratio values vary according to the defined input parameters, and to understand whether changing these parameters is better able to highlight the presence of sub-horizontal denudation surfaces. Third, it is important to evaluate whether the altitudinal ranges previously ascribed to sub-horizontal denudation surfaces in Wales can be corroborated using this technique.

3. BACKGROUND

3.1 THE ELEVATION-RELIEF RATIO

The elevation-relief ratio was developed as a terrain parameter that was able to define geometric characteristics without particular emphasis on formative processes (Wood & Snell 1960). Until recently the principal limitation of this technique related to the amount of time needed in order to generate the required data, especially over large areas; this has meant that very few studies have attempted to apply this geomorphological parameter. However, advances in GIS mapping software have enabled the elevation-relief ratio to be calculated over far larger areas and at far more detailed spatial resolutions than was previously possible.

The elevation-relief ratio is derived from the following equation:

$$Elevation - relief\ \ ratio\ (H) = \frac{Mean\ elevation - Minimum\ elevation}{Maximum\ elevation - Minimum\ elevation}$$

(Equation 1)

From this equation, possible solutions must always be greater than 0.00 and less than 1.00, as the mean elevation minus the minimum elevation can approach the relative relief value but never equal it; indeed, Pike & Wilson (1971) demonstrated that the elevation-relief ratio is mathematically analogous to the more complex hypsometric integral of Strahler (1952). The elevation-relief ratio subsequently came to be regarded either as a measure of the extent to which topography has been opened up by erosion (Clarke 1966) or as a measure of the degree of landscape dissection (Evans 1972). Values close to 0.00 or 1.00 both represent sub-horizontal topography; a value nearer 0.00 is indicative of concavity or sub-horizontal terrain with some isolated peaks, whereas a value nearer 1.00 is indicative of convexity or sub-horizontal terrain with deep incision. Using this attribute, it is thus possible to mathematically distinguish between, say, valley lowlands and dissected upland plateaux in a manner that cannot be achieved using slope angle or relative relief. Elevation-relief ratio values generally range between 0.15 and 0.85, with clustering between 0.40 and 0.60 (Pike & Wilson 1971); therefore, in this paper it is considered that elevation-relief ratio values between 0.00-0.40 and 0.60-1.00 both represent sub-horizontal surfaces, but that only those values between 0.60-1.00 represent sub-horizontal denudation surfaces as it is these that are characterized by a generally convex morphology.

3.2 THE DENUDATION SURFACES OF WALES

Few recent studies have undertaken sub-horizontal denudation surface mapping in Wales, despite the presence of conspicuously sub-horizontal landscape components. Where such mapping does exist, it has generally only been undertaken in areas of limited spatial extent at low to medium elevations (*e.g.* Miller 1935, 1937, 1938; Brown 1950; Embleton 1964). The only previous attempt to define the complete suite of sub-horizontal denudation surfaces in Wales was that of Brown (1960); surfaces were mapped through the integration of topographic map analysis and field investigation. In that study, evidence was presented for the existence of three widespread sub-horizontal denudation surfaces above 200 m asl. The "*Low Peneplain*" was mapped at between 210-330 m asl; this surface was thought to be most frequently observed at between 210-270 m asl and again between 300-330 m asl. The "*Middle Peneplain*" was mapped at between 365-485 m asl; this surface was thought to be most frequently observed at between 365-425 m asl. The "*High Plateau*" was mapped at between 515-575 m asl, and this surface was considered to increase to 610 m asl around any residual hills. In addition, a fourth surface was thought possible due to a postulated "*Summit Plain*" between 635-1,060 m asl. Brown (1960) stated that "each peneplain is traceable throughout the length and breadth of Wales … [and] there is no evidence that any of the three peneplains has been warped" (p. 103 & p. 104); if such an assertion is correct, it may be hypothesized that these features would be readily discernible from DEM analysis. Indeed, future studies were pre-empted when it is suggested that "…this work is a pioneer attempt to map the upland plains of Wales, but it is only that, and more detailed mapping is both possible and desirable" (Brown 1960 p. 60).

4. METHODOLOGY

The methodology of any study of landscape evolution that incorporates innovative computational techniques must be clearly outlined. In order to determine the elevation-relief ratio using ESRI ArcMap 9.2, the map layers detailed in this section are required. However, in some instances these layers do not appear on any of the final elevation-relief ratio maps (*i.e.* the planar surface maps) but form a critical element of the construction process; describing the construction of such layers is important to ensure that this methodology is entirely repeatable.

4.1 THE SRTM DEM

The gridded topographic dataset used in this study is the NASA SRTM DEM, which has a horizontal resolution of 3 arc-seconds (*c*. 90 m x *c*. 90 m) and a vertical error of less than 16 m; the geographic coordinate system is provided by WGS-84 datum. SRTM data are known to be affected by mountain and desert no-data areas (“voids”); although these amount to no more than 0.2% of the total area surveyed, such voids can be problematic in areas of high relief or deep dissection. To counter this, the SRTM data provided on the CGIAR-CSI GeoPortal (srtm.csi.cgiar.org) has been processed to fill these data voids; the SRTM DEM files available on the CGIAR-CSI GeoPortal have been mosaiced into a seamless global coverage of 5 degree x 5 degree tiles. The requisite files were downloaded as ASCII files and converted to raster files in ESRI ArcMap 9.2, using the “*Conversion Tools*” function within “*ArcToolbox*”; the raster files were then stitched together using the “*Mosaic*” function.

4.2 MAXIMUM, MEAN & MINIMUM PLANAR SURFACE MAP LAYERS

Planar surface layers were constructed using the “*Focal Statistics*” function within “*Spatial Analyst*”. This function calculates the pertinent focal statistics from the input SRTM DEM within a specified distance of the centre cell within a circular neighbourhood; the radius of the circle is measured from the centre cell perpendicular to the *x*- or *y*- axis. For each of the defined circular neighbourhoods (3, 6, 12, and 24 grid cells), three output gridded topographic datasets were constructed from the SRTM data; these relate to the maximum (*e.g.* Figure 2a), mean (*e.g.* Figure 2b), and minimum (*e.g.* Figure 2c) focal statistics.

4.3 DETERMINING THE ELEVATION-RELIEF RATIO

To construct elevation-relief ratio map layers, the three input planar surface map layers outlined previously are required as these effectively constitute the terms needed to satisfy the elevation-relief ratio (Equation 1); this requires two separate stages to be undertaken. In the first stage, the numerator and denominator terms were established using the “*Raster Math*” function in “*3D Analyst*”. This function calculates a per-cell statistic from multiple raster layers, with “*Minus*” used to calculate the range of values that separate (i) the mean elevation and the minimum elevation (*e.g.* Figure 2d), and (ii) the maximum elevation and the minimum elevation (*e.g.* Figure 2e); thus, the two output rasters numerically satisfy the numerator and denominator terms in the elevation relief ratio. In the second stage, these two rasters were divided in order to satisfy the elevation-relief ratio, using the “*Divide*” function in “*Raster Math*”. The raster that corresponds to the numerator was used as “*Input Raster 1*”, whilst the raster that corresponds to the denominator was used as “*Input Raster 2*”; the output floating-point raster layer is a graphic representation of the elevation-relief ratio (*e.g.* Figure 2f).

Using this map layer, it was then possible to convert those elevation-relief ratio values within the defined sub-horizontal category (*i.e.* less than or equal to 0.40 and equal to or greater than 0.60) back into an elevation raster. These data had to be converted to integer raster v’alues as the elevation-relief ratio layer is comprised of floating point data. First, all values were multiplied by 1000 using “*Times*” in “*Raster Math*”. Second, this floating point data file had to be converted to an ASCII file using “*Raster to ASCII*” in “*Conversion Tools*” and then reconverted back into an integer raster data file using “*ASCII to Raster*” in “*Conversion Tools*”. Thus, the elevation-relief values were now presented as integers between 0 and 1000. Thereafter, elevation-relief ratio values of less than or equal to 0.40 and equal to or greater than 0.60 were removed in two separate stages using “*Extract by Attributes*” in the “*Spatial Analyst*” toolbox, with the clauses “Value = greater than 400” and “Value = less than 600”. These two raster files were then merged using the “*Mosaic to New Raster*” in “*Spatial Analyst*”. This sub-horizontal elevation-relief ratio raster layer was converted into elevation data using “*Extract by Mask*” function in “*Spatial Analyst*”, where the DEM was used as the “*Input Raster*” and the sub-horizontal relative relief raster layer was used as the “*Input Feature Data Mask*”. The output raster layer is an elevation map of only those areas that had previously been ascribed an elevation-relief ratio value of either less than or equal to 0.40 or equal to or greater than 0.60.

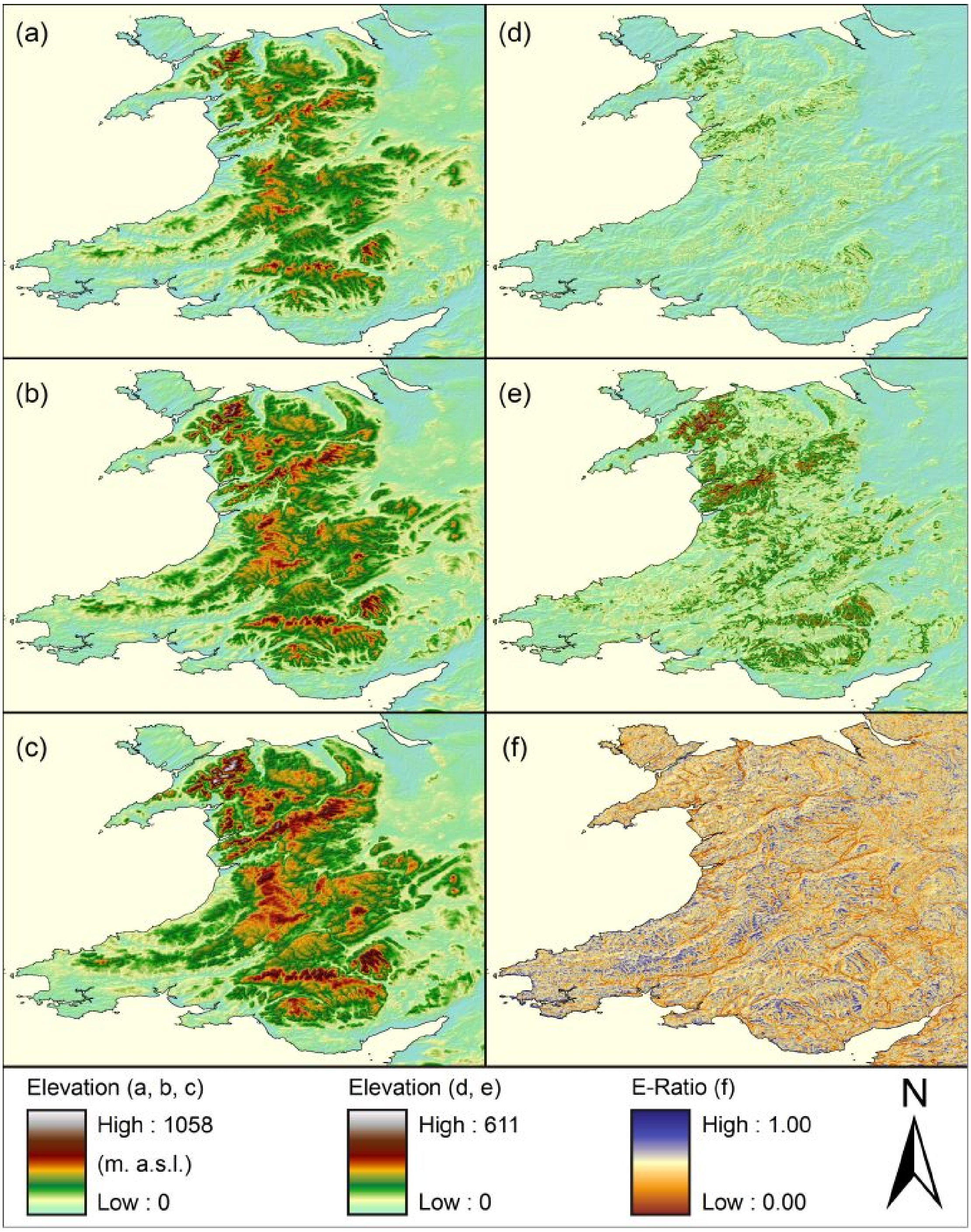

Figure 2 - The minimum (Figure 2a), mean (Figure 2b), and maximum (Figure 2c) planar surface map layers derived from the SRTM DEM, determined from a circular neighbourhood with a radius of 6 grid cells; the mean planar surface layer minus the minimum planar surface layer (Figure 2d); the maximum planar surface layer minus the minimum planar surface layer (Figure 2e); an elevation-relief ratio map (Figure 2f), produced by dividing the values depicted in Fig. 2d with the values depicted in Fig. 2e (see Equation 1).

5. RESULTS

In this paper, the Welsh region is delineated by the 53º30’00"N to the north and 51º18’15"N to the south, 2º23’50"W to the west and 5º23’50"W to the east. The principle physiographic regions were divided into mountains, dissected plateaux, hills, valley lowlands, coastal plateaux, and coastal flats in the study of Brown (1960); that classification is considered to represent a valuable approximation of the Welsh landscape. A map of these relief regions is shown in Figure 3; a detailed discussion on the underlying rationale can be found in Brown (1960).

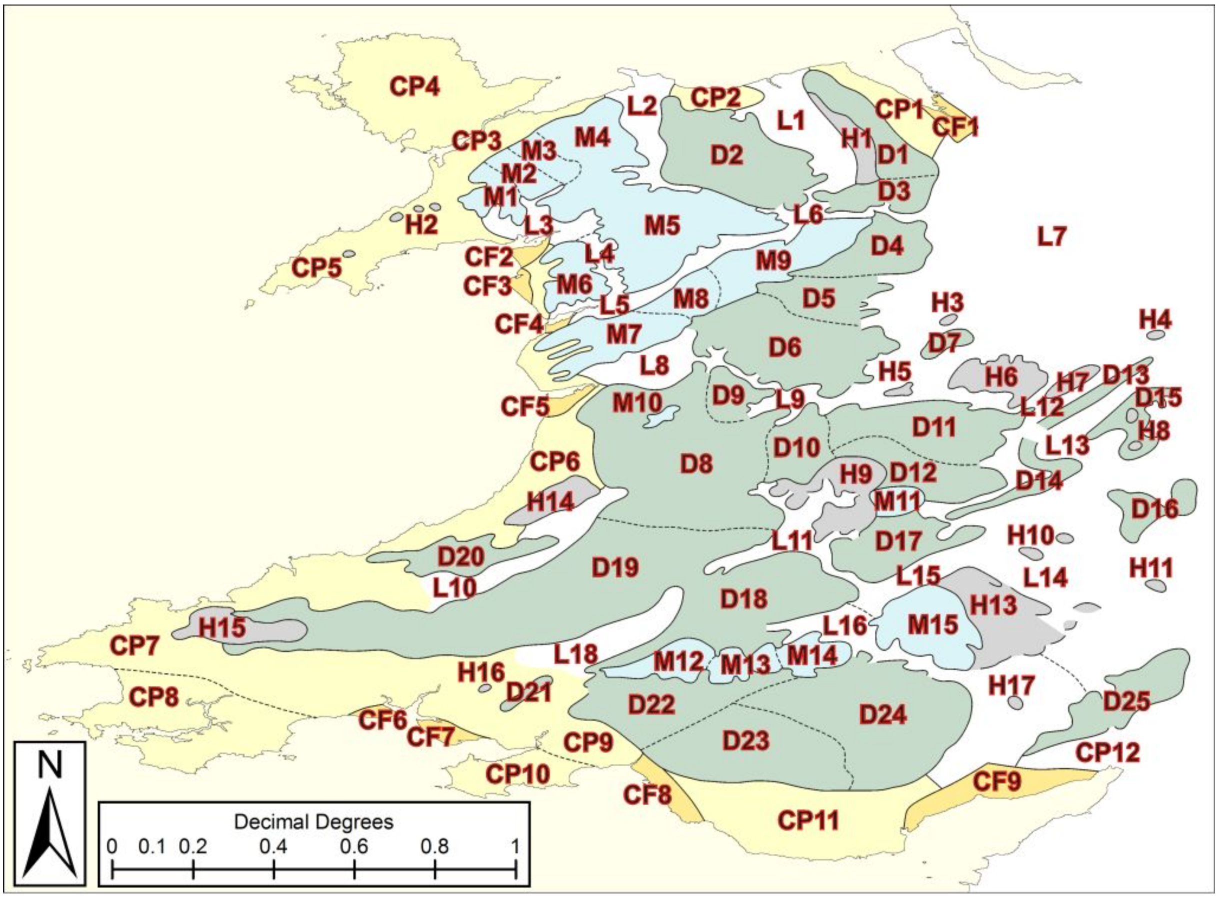

Figure 3 - A location map of the principal relief regions in Wales, redrawn with a modified taxonomy from that of Brown (1960); the names of the relief regions are given overleaf.

Mountains (M)		**Coastal Plateaux (CP)**		**Dissected Plateaux (D)**	
M1	Hebog mass	CP1	Flintshire	D1	Halkyn Mountain
M2	Snowdon mass	CP2	Denbighshire	D2	Denbighshire Moors
M3	Glyder mass	CP3	Arfon	D3	Cyrn y Brain
M4	Llywelyn mass	CP4	Anglesey	D4	Pen y Gwely
M5	Arenig mass	CP5	Ll?n	D5	Yr Allt Boeth
M6	Rhinog mass	CP6	Ceredigion	D6	Garreg Hîr
M7	Cadair Idris mass	CP7	Northern Pembs. & Carmarthenshire	D7	Long Mountain
M8	Aran mass			D8	Central Wales
M9	Berwyn mass	CP8	South Pembrokeshire	D9	Trannon
M10	Plynlimon	CP9	Swansea district	D10	Rhyd Hywel
M11	Radnor Forest	CP10	Gower	D11	Clun Forest
M12	Mynydd Du	CP11	Vale of Glamorgan	D12	Beacon Hill
M13	Fforest Fawr	CP12	Forest of Dean	D13	Wenlock Edge
M14	Brecon Beacons			D14	Aymestry

M15 Black Mountains

Hills (H)

H1 Clwydian Range
H2 Ll?n
H3 Breidden
H4 Wrekin
H5 Cefn Coed
H6 Shelve & Longmynd
H7 Caer Caradoc
H8 Clee
H9 Carneddau
H10 Burton & Westhope
H11 Woolhope
H12 Malvern
H13 Monnow
H14 Mynydd Bach
H15 Mynydd Preseli
H16 Mynydd Llangyndeyrn

Valley Lowlands (L)

L1 Clwydian lowland
L2 Conwy lowland
L3 Ffestiniog lowland
L4 Trawsfynydd lowland
L5 Mawddach lowland
L6 Upper Dee lowland
L7 Cheshire Plain
L8 Dyfi lowland
L9 Vale of Powys
L10 Teifi lowland
L11 Builth lowland
L12 Ape Dale lowland
L13 Corve Dale lowland
L14 Hereford Plain
L15 Wyevale lowland
L16 Upper Usk lowland
L17 Tywi lowland
L18 Lower Usk lowland
L19 Vale of Gloucester

D15 Clee Hills Fringe
D16 Bromyard
D17 Red Hill
D18 Mynydd Epynt
D19 Teifi-Tywi interfluve
D20 South Ceredigion
D21 Mynydd Sylen
D22 Western coalfield
D23 Central coalfield
D24 Eastern coalfield
D25 Forest of Dean

Coastal Flats (CF)

CF1 Dee Estuary
CF2 Morfa Harlech
CF3 Morfa Dyffryn
CF4 Rô Wen
CF5 Cors Fochno
CF6 Laugharne Burrows
CF7 Pembrey Burrows
CF8 Kenfig Burrows
CF9 Caldicot Levels

Figure 4 depicts elevation-relief ratio maps determined from the four circular neighbourhoods outlined previously; 3 (Figure 4a), 6 (Figure 4b), 12 (Figure 4c), and 24 grid cells (Figure 4d). Thereafter, the most salient aspects of Figure 4 are presented in Figure 5; those maps presented in column (i) depict all the areas defined as sub-horizontal surfaces through the application of the elevation-relief ratio (*i.e.* those areas with elevation-relief ratio values of less than or equal to 0.40 and equal to or greater than 0.60), whilst the maps presented in column (ii) depict only the areas defined as sub-horizontal denudation surfaces through the application of the elevation-relief ratio (*i.e.* those areas with elevation-relief ratio values of equal to or greater than 0.60); again, the rows (a-d) represent the size of the circular neighbourhoods (3, 6, 12, and 24 grid cells respectively). Figure 6 depicts the elevations of those areas defined as sub-horizontal in Figure 5; the layout of Figure 5 is repeated exactly in Figure 6.

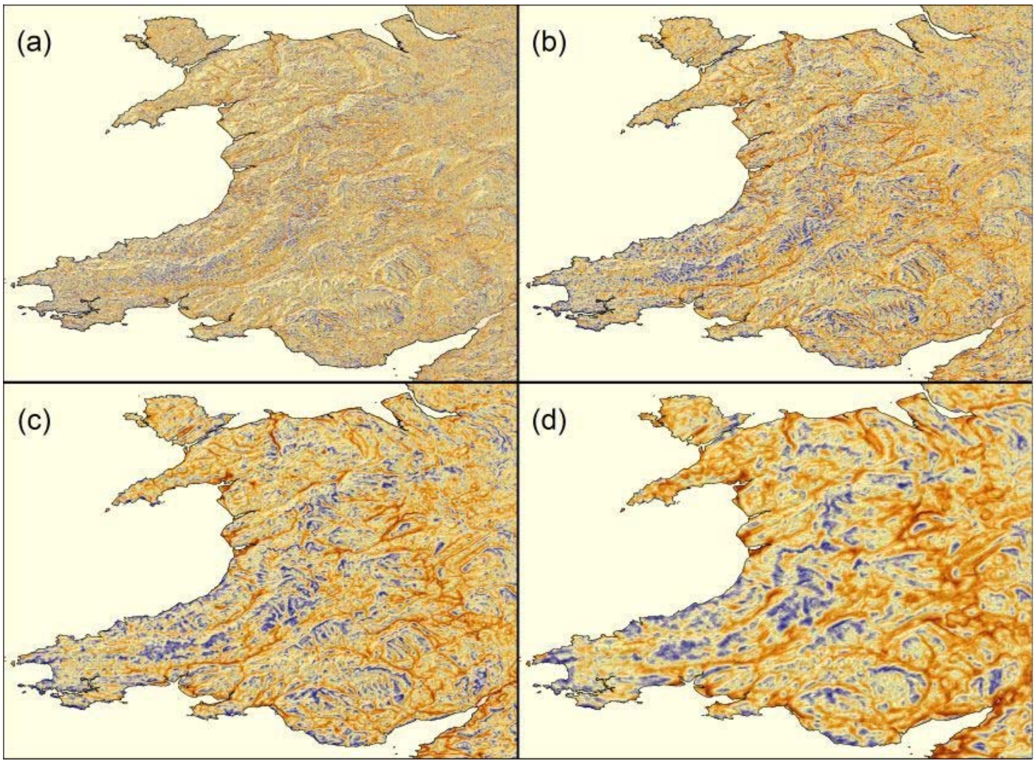

Figure 4 - Elevation-relief ratio maps of Wales. Figures 4a, 4b, 4c, and 4d have been determined from circular neighbourhoods with radii of 3 (*c*. 270 m), 6 (*c*. 540 m), 12 (*c*. 1080 m), and 24 grid cells (*c*. 2160 m) respectively. For scale, see Figure 5.

5.1 SUB-HORIZONTAL SURFACES DEFINED BY THE E-R RATIO

Figures 4 and 5 (a-i, b-i, c-i, d-i) demonstrate that the lowest elevation-relief ratio values are associated with the valley lowland relief regions. This characteristic is especially notable in valleys that have been deeply incised below the general topographic surface; prominent examples include the valleys of Clwyd (L1), Conwy (L2), Dyfi (L8), upper Teifi (L10), Tywi (L17), and the lower Usk (L18). It is particularly important to note that low elevation-relief ratio values are not a function of low elevation; for example, many coastal plateaux are characterized by intermediate values (*e.g.* Northern Pembrokeshire & Carmarthenshire (CP7) and South Pembrokeshire (CP8)). Nonetheless, some coastal plateaux are characterized by low elevation-relief ratios (*e.g.* Llwn (CP5)); however, the low values observed there actually reflect the presence of the Llwn Hills (H2) thereabouts, which appear as residual hills above the aforementioned coastal plateau; a similar, although less pronounced, pattern is observed on the adjacent coastal plateau of Anglesey (CP4).

The highest elevation-relief ratio values shown in Figures 4 and 5 (a-ii, b-ii, c-ii, d-ii) are most frequently associated with dissected plateaux, although occasionally such values may be connected to hills or coastal plateaux. An almost continuous belt of high elevation-relief values may be traced in an elliptical pattern parallel to the Cardigan Bay coastline; this belt incorporates the dissected plateaux of Garreg Hîr (D6), Trannon (D9), Central Wales (D8), and the Teifi-Tywi interfluve (D19). In the south, the dissected plateaux of Mynydd Epynt (D18), the Central Coalfield (D23), the Eastern Coalfield (D24) and the Forest of Dean (D25) are all associated with high elevation-relief ratio values, despite disparate elevations. High elevation-relief ratio values are also associated with some hills and mountains, where the summits exhibit a *mesa*-like form; for example, the hills of Caer Caradoc (H7) and the mountain mass of Radnor Forest (M11) have notably high elevation-relief ratio values.

Conversely, although many hills are only associated with intermediate elevation-relief ratio values where their summits do not exhibit a *mesa*-like form, such features may be identified by low elevation-relief ratio values in the surrounding vicinity; an example of this has already been noted from the Llwn Hills (H2), and it is also seen in the east of the study area (*e.g.* Wrekin (H4), and Burton & Westhope (H10)). High elevation-relief ratio values may also be associated with coastal plateaux, where there is a sufficient convexity in the landscape; such convexities may be associated with either deep linear incision or high cliff sections, depending on local circumstance. However it is more common for cliff sections to cause these high elevation-relief ratio values; prominent examples can be observed along the coastal plateaux of Ceredigion (CP6), Northern Pembrokeshire & Carmarthenshire (CP7), and Southern Pembrokeshire (CP8).

The size of the circular neighbourhood influences the size horizontal area but it does not significantly influence the altitudinal range over which these surfaces occur. The horizontal landscape component varies from a maximum of 6,027 km^2 where the elevation-relief ratio was determined from a circular neighbourhood with a radius of 6 grid cells, to a minimum of 2,802 km^2 where the elevation-relief ratio was determined from a circular neighbourhood with a radius of 24 grid cells (Table 1). There is no clear correlation between the size of the circular neighbourhood and sub-horizontal surface area; however, generally the surface area decreases as the circular neighbourhood increases.

Table 1 - The sub-horizontal surface area of Wales, calculated using the elevation-relief ratio.

Size of circular neighbourhood in grid cells)	Total surface area (km^2)	Total sub-horizontal surface area (km^2)	Percentage of total surface area (%)	Total sub-horizontal denudation surface area (km^2)	Percentage of total surface area (%)
3 (*c.* 270 m)	39,758	4,941	12.43	1,526	3.83
6 (*c.* 540 m)	39,758	6,027	15.16	1,805	4.54
12 (*c.* 1080 m)	39,758	4,389	11.04	1,048	2.64
24 (*c.* 2160 m)	39,758	2,802	7.48	424	1.07

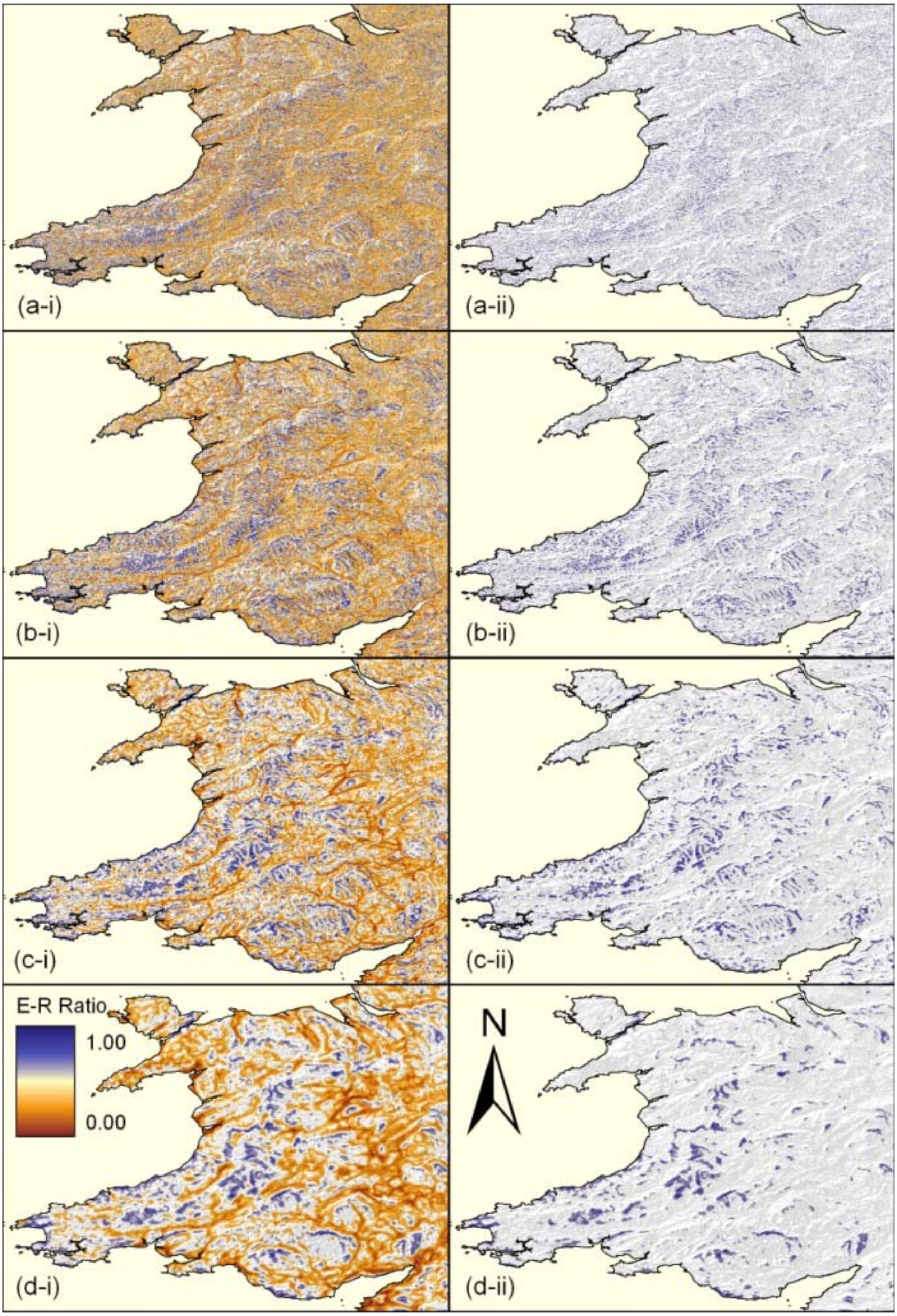

Figure 5 - Sub-horizontal surfaces (a-i to d-i (left)) and sub-horizontal denudation surfaces (a-ii to d-ii (right)) defined by the elevation-relief ratio; a, b, c, and d have been determined from circular neighbourhoods with radii of 3 grid cells (*c*. 270 m), 6 grid cells (*c*. 540 m), 12 grid cells (*c*. 1080 m), and 24 grid cells (*c*. 2160 m) respectively.

5.2 THE ALTITUDINAL RANGE OF SUB-HORIZONTAL SURFACES

In order to constrain the vertical extent of any sub-horizontal denudation surfaces, altitude-frequency histograms have been constructed (Figure 7). Initially the most conspicuous characteristic of this histogram is that the altitudinal peaks become increasingly prominent both as the histograms move from elevation (Figure 7a), through to sub-horizontal surfaces (Figures 7b, 7c, 7d, 7e), and then sub-horizontal denudation surfaces (Figures 7f, 7g, 7h, 7i), and as the size of the circular neighbourhood increases (*i.e.* from b-e and from f-i); thus, the most readily defined sub-horizontal denudation surfaces are observed in Figure 7i, in which the elevation-relief ratio was determined from a circular neighbourhood with a radius of 24 grid cells.

Despite the differences in horizontal surface area described in the previous section, changing the size of the circular neighbourhood does not have a marked influence on the altitudinal range occupied by sub-horizontal denudation surfaces; however, such surfaces do become progressively more pronounced as the size of the circular neighbourhood increases. For example, those sub-horizontal denudation surfaces recognized where the elevation-relief ratio was determined from a circular neighbourhood with a radius of 24 grid cells can be observed in the other histograms, but usually only to a far lesser extent; however, such surfaces are difficult to recognize within the altitude-frequency histogram of Wales.

In this study four sub-horizontal denudation surfaces are shown at lower elevations in the altitude-frequency histograms; the prominence of these surfaces decreases with elevation. The surfaces are defined at 40-90 m asl, 118-132 m asl, 173-187 m asl, and 219-229 m asl. Furthermore, a single sub-horizontal denudation surface is shown at higher elevations in the altitude-frequency histograms at between 385-520 m asl; it is thought that the wide elevation range that characterizes this surface may be a consequence of tilting.

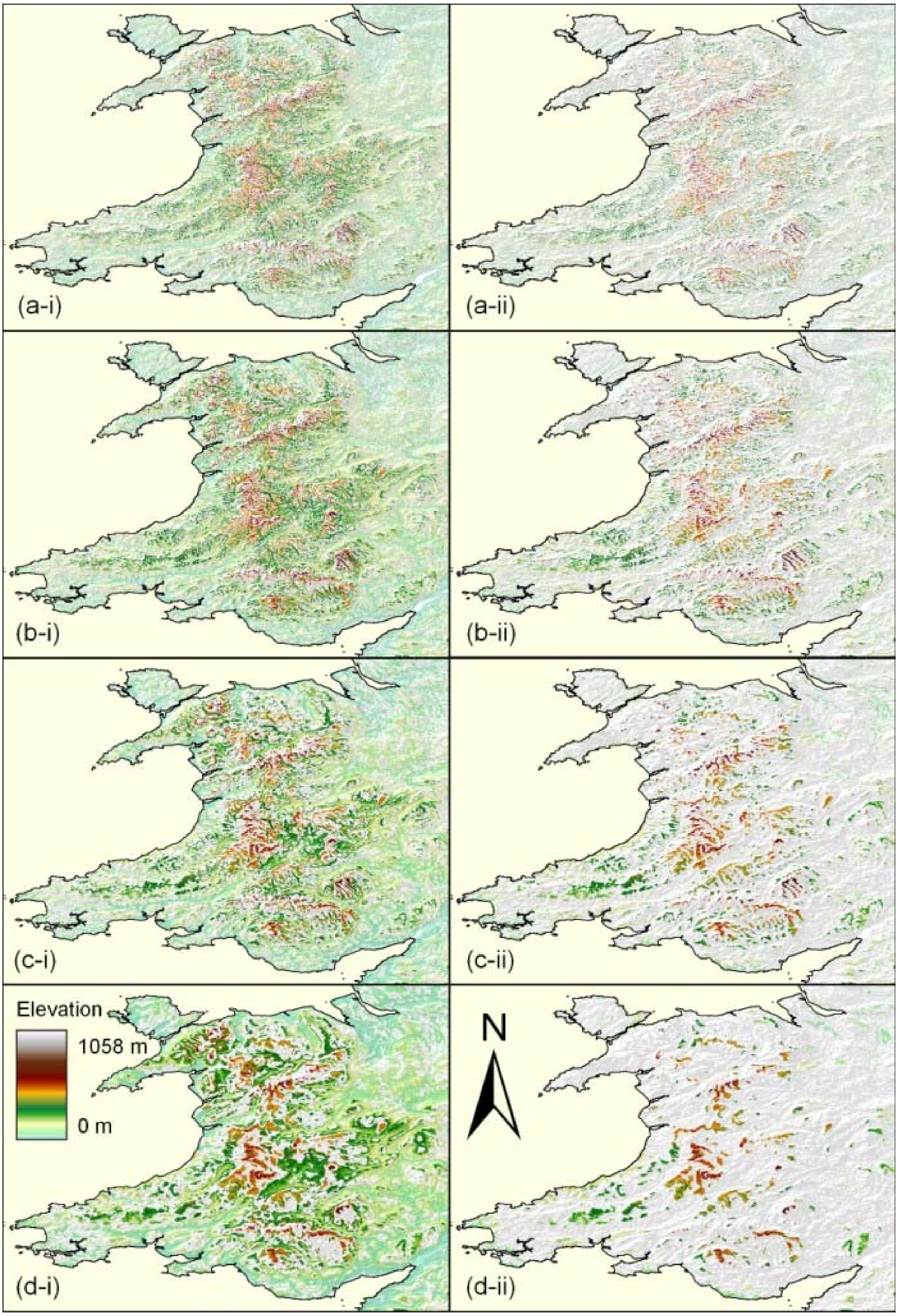

Figure 6 - Elevation maps of those sub-horizontal surfaces (a-i to d-i (left)) and sub-horizontal denudation surfaces (a-ii to d-ii (right)) defined by the elevation-relief ratio (see Figure 5); a, b, c, and d have been determined from circular neighbourhoods with radii of 3 grid cells, 6 grid cells, 12 grid cells, and 24 grid cells respectively.

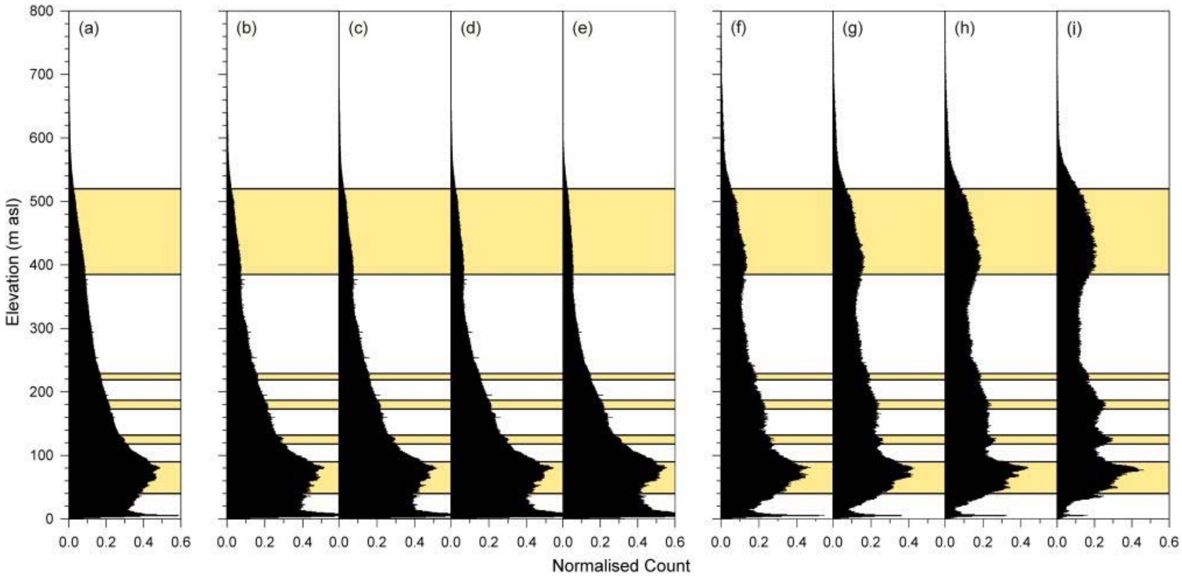

Figure 7 - Altitude-frequency histogram of Wales (Figure 7a); altitude-frequency histograms of sub-horizontal surfaces defined by the elevation-relief ratio, determined from circular neighbourhoods with radii of 3 (Figure 7b), 6 (Figure 7c), 12 (Figure 7d), and 24 grid cells (Figure 7e); altitude-frequency histograms of sub-horizontal denudation surfaces defined by the elevation-relief ratio, determined from circular neighbourhoods with radii of 3 (Figure 7f), 6 (Figure 7g), 12 (Figure 7h), and 24 grid cells (Figure 7i).

6. SUMMARY

The overall aim of this paper was to demonstrate the value of the elevation-relief ratio as a geomorphological tool, which is able to analytically identify sub-horizontal denudation surfaces within the heavily dissected landscape of Wales. An analytical mapping technique such as the elevation-relief ratio is a formal scientific construction aimed at rationalizing that which may be observed in the field; after all, "…most people who are not blind or stupid can tell when they are in an area of relatively flat country" (Ollier 1981).

In order to calculate the elevation-relief ratio using ESRI ArcMap 9.2, the maximum, mean, and minimum planar surface map layers had to be determined from the input SRTM DEM; the layers were constructed using a range of circular neighbourhoods, with radii of 3, 6, 12, and 24 grid cells. These layers are able to satisfy the numerator and dominator terms of the elevation-relief ratio, and the elevation-relief ratio maps were constructed. From this map, those areas that fell within the sub-horizontal range (less than or equal to 0.40 or equal to or greater than 0.60) were extracted; these threshold values are underpinned by evidence derived from Wood & Snell (1960) and Pike & Wilson (1971), and aids methodological replicability in future studies. Using only those areas defined as sub-horizontal, elevation maps were constructed and the altitudinal range of such surfaces was constrained more closely using altitude-frequency histograms.

It is very difficult to reconcile the results described here with the tripartite classification of Brown (1960); in that study, evidence was presented for the existence of three widespread sub-horizontal denudation surfaces at between 210-330 m asl, 365-485 m asl, and 515-575 m asl. Clearly those surfaces recorded at between 40-90 m asl, 118-132 m asl, and 173-187 m asl fall below the "*Low Peneplain*" of Brown (1960); the surface at between 219-229 m asl is also unlikely to correspond with the "*Low Peneplain*" because the altitudinal range ascribed to that surface is an order of magnitude greater than the surface recognized here.

Nonetheless, the most significant results obtained here pertain to the uppermost surface, with an altitudinal range of between 385-520 m asl; clearly this surface corresponds most closely with the "*Middle Peneplain*" of Brown (1960), although there is also some altitudinal overlap with the "*High Peneplain*". There is a large discrepancy between the size of the altitudinal range occupied by the uppermost surface and those described at lower elevations; the large altitudinal range may be caused by (i) the erosional destruction of a suite of sub-horizontal denudational surfaces, which has meant that no clear signature of this suite remains visible within the altitude-frequency histograms or (ii) a previously widespread sub-horizontal denudation surface has been subjected to tilting, which has caused its altitudinal range to become elongated in the histogram. The latter interpretation is preferred based on previous studies (Rowberry et al, 2007; Rowberry 2007); if this interpretation is correct, the formation of sub-horizontal denudation surfaces at lower levels must have occurred after the widespread tilting event.

This study has shown that it is possible to apply an analytical mapping technique to the SRTM DEM within a GIS framework, in order to constrain the vertical and horizontal extent of sub-horizontal denudation surfaces in Wales. The application of an analytical mapping technique has two notable advantages over earlier field mapping (*e.g.* Miller 1935, 1937, 1938; Brown 1950, 1960; Embleton 1964). First, the criteria used to define sub-horizontality are able to withstand critical examination because the need for subjective decision making is more-or-less removed from the mapping process. Second, exactly the same methodology can be applied to a wide range of geological and tectonic settings; therefore if the same technique is used, results obtained in this study should be directly comparable to those results derived from analogous passive continental margin settings around northwest Europe. These two advantages represent a significant improvement in the scientific rigour with which sub-horizontal denudation surfaces are mapped, and such advances have been achieved as a direct result of the advent of global DEMs.

7. CONCLUSIONS

- The recent upsurge in studies of long-term landscape evolution has been stimulated by the advent of high resolution digital elevation models, such as the SRTM DEM; these have enabled enduring physical models to be tested with considerably greater scientific rigour than was previously possible.

- The elevation-relief ratio provides a powerful, yet simple, tool with which to identify sub-horizontal denudation surfaces within heavily dissected landscapes. For the first time, it is now possible to calculate the elevation-relief ratio over large areas within a GIS framework.

- Five sub-horizontal denudation surfaces are recognized within the Welsh region, at between 40-90 m asl, 118-132 m asl, 173-187 m asl, 219-229 m asl, and 385-520 m asl; the altitudinal range of these surfaces has never been described in any previous study.

- The enduring tripartite division of the Welsh landscape envisaged by Brown (1960) must now be rejected, both in terms of the number of surfaces that may be recognized and their altitudinal range.

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