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SOURCES OF GEOMORPHOLOGICAL DIVERSITY IN THE TROPICS

Michael F. Thomas

Biological & Environmental Sciences - School of Natural Sciences - University of Stirling - Stirling - Scotland, FK9 4LA - e-mail: m.f.thomas@stir.ac.uk

Abstract

The concept of geodiversity has its roots in the fossil record as part of the Earth's biodiversity and in the need for conservation of fossil localities and other sensitive geological sites. The geomorphological component of geodiversity is central to landscape conservation and is examined as a response to the operation of magmatic and surface processes interacting over long time periods. Differentiation of landforms can arise directly from formational processes or develop over time as result of varying sensitivity to earth surface processes. In the tropics, the susceptibility of rocks to chemical weathering is a key source of geomorphic diversity, particularly in the denudation of geologically stable terrains. The accumulation of weathering products as duricrusts, and as quartz sands can, however, can lead to reduction in both geodiversity and biodiversity, locally and regionally. Numerical methods for quantifying geomorphological diversity need to take account of these factors. The unique features of many iconic landforms also add to the difficulties of using terrain indices of geomorphic diversity derived from digital elevation models.

Keywords: Biodiversity; geodiversity; geomorphological diversity; landscape sensitivity; differential weathering.

Introduction

The concept of *biodiversity* has been current in scientific thinking for more than two decades, and arguably springs from Darwinian analysis of the natural world. It embodies a view of nature as a series of complex, interacting and interdependent systems, and it fits neatly into the concept of the *Gaia* (LOVELOCK, 1979). The first serious exploration of the state of global biological diversity and use of the term 'biodiversity' is attributed to Wilson (1988). In that volume Wilson expressed the widespread concern about the conservation of biodiversity and the important contribution of tropical forests to global biodiversity.

For Charles Darwin and other evolutionary biologists, essential aspects of global biodiversity could only be understood by reference to the fossil record, and concern amongst earth scientists regarding the conservation of important fossil localities has been a major motive for geological conservation although, as noted by Gray (2004) in his wide ranging book on Geodiversity, concerns were expressed about the preservation of erratic boulders and about sensitive scenic sites in 19th century Europe. The promotion of *geodiversity* as a term to rank alongside biodiversity has, however, been recent and restricted to comparatively few countries. According to Gray (2008) the term was used first in Tasmania in 1996 (see also HOUSHOLD & SHARPLES, 2008), and subsequently developed by the Nordic countries (NORDIC COUNCIL OF MINISTERS, 2000, 2003) to include both geological and geomorphological features and processes.

Studies of biodiversity and geodiversity have been developed in part as instruments of conservation policy, and the application of these concepts has spread particularly within national and international agencies responsible for World Heritage Areas, national parks and many smaller regional areas and sites. Yet few of these areas have been designated exclusively (and sometimes not at all) for their biodiversity, and many are effectively areas of outstanding landscape. Geographers have discussed *landscape* for more than a century and it was a geographer, Carl Troll (1963), who developed ideas in *landscape ecology* (*Landschaftsöekologie*) for land management, and this field of study, with its concern for patterns, processes and scales, has also developed in the intervening decades (WIENS & MOSS, 2005). Arguably, however, the major scientific and theoretical discussions about diversity in the natural world have remained in the field of biology. Links between biodiversity and geodiversity are intuitively important and Schmidt (1998), for example, found that *phytodiversity* on Mediterranean islands reflects the „physiographic complexity of the islands. In a similar manner two studies carried out respectively at the patch and landscape scales on Rhode Island, U.S.A., found clear links between geomorphological heterogeneity and biotic diversity (BURNETT *et al*., 1998; NICHOLS *et al*., 1998).

Most conservation-based studies also take account of human impacts on landscape, and the British Geological Survey uses Stanley's (2001) definition of geodiversity as, "the link between people, landscape and their culture: it is the variety of geological environments, phenomena and processes that make those landscapes, rocks, minerals, fossils and soils which provide the framework for life on earth". According to the BGS, it embraces: the inter-relationship between geology and other interests; representative sites where the area's geological deposits and features may be seen; the historical legacy of geological research within the area; sites and features currently used in interpreting earth science; past and present mineral workings; the influence of geology in shaping the man-made environment, plus materials, collections and other records, including published literature and maps. Gray (2004) is more specific and adapts a version of the Australian Natural Heritage Charter: "Geodiversity is the natural range (diversity) of geological (rocks minerals, fossils), geomorphological (landform, processes) and soil features. It includes their assemblages, relationships, properties, interpretations and systems" (GRAY, 2004, p.8). He describes geodiversity according to well established principles of physical geology and geomorphology but is mainly concerned with valuing, conserving and managing geodiversity. Increasing interest in geological conservation has led to other reviews of this field (BURECK & PROSSER, 2008), and Gray (2008, p 288) has gone further, to claim that "geodiversity unquestioningly has attained the status of a significant geological paradigm". This claim is based on his view that the study of geodiversity now has a theoretical framework of related ideas within which scientific research is carried out.

As a scientific tool, however, the study of geodiversity has not gained universal support. The United States Geological Survey, for example, makes very few references to geodiversity or its applications and, while the concept of geodiversity has already proved valuable in raising awareness of conservation issues in the earth sciences, including geomorphology, in its present stage of development and understanding it does not stand alongside biodiversity as a unifying concept for study of the abiotic environment. The place of geomorphology within discussions of geodiversity can either be marginal (where fossil localities are identified for conservation e.g.) or central (where the landscape expresses geological structures and rocks), and a great deal depends on the scale of enquiry.

In this paper the sources of geomorphological (or geomorphic) diversity (which is an expression of complexity or heterogeneity) rather than its description will be the focus of discussion, and examples will be drawn mainly from tropical and sub-tropical environments.

Geomorphic complexity as a component of geodiversity

Geodiversity has a number of definable components, as shown in Figure 1.

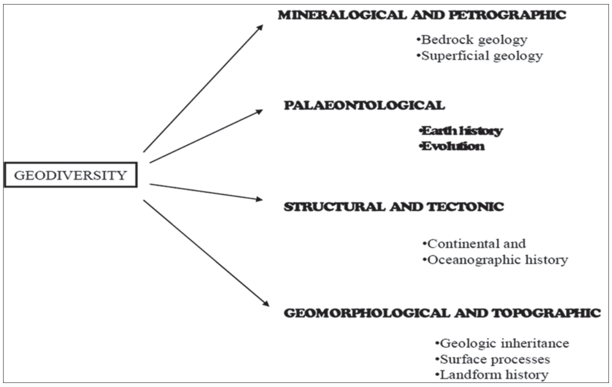


Figure 1 - Components of geodiversity.

Both mineralogical and palaeontological diversity refer to the content and character of rocks and rock formations. Igneous rocks with magmatic sources contain no fossils life forms and most minerals have formed under high pressures and temperatures, and in the absence of an atmosphere. Volcanic rocks are initially similar but may solidify in contact with atmospheric and biotic elements of the environment. Sedimentary rocks are the products of atmospheric and biotic intervention: including weathering, and all forms of transport and deposition. Metamorphic transformation creates new mineralogical provinces and individual rock types, and returns surviving biotic materials to an abiotic state as fossils. Thus minerals and rocks reflect the diversity of processes involved in lithogenesis. Those that retain biotic forms as fossils contain the basic elements of earth history: revealing evolutionary stages, environmental conditions, including catastrophes and extinctions, as well as the transformation of the primitive atmosphere towards our familiar envelope. The settings of rock formations and their rock mass structures provide dramatic evidence of the forces that have shaped continents, island arcs and ocean basins. The stress fields involved in crustal upheaval are displayed as fracture systems and as great fault and fold systems.

The geodiversity that is a product of these processes, events and evolutionary history is also expressed in the elevation and depression of the landsurface, and in the accumulation of volcanic cones and lavas, and sedimentary features such as alluvial and lacustrine plains and deltas. But to account for many major landforms and landscape details the understanding of geomorphology is necessary. The study of landforms has long contained two traditions: the older, evolutionary geomorphology views landscapes as progressing through stages towards the elimination of relief. In Davis' (1899a) interpretation of the geographical cycle, relief (landform diversity) at the start of a cycle will be progressively reduced with time. By contrast, dynamic geomorphology with its roots in the work of Gilbert (1877, 1914), examines the processes that transform landscapes over shorter time periods, and can be used to predict outcomes on measurable timescales (floods, landslides, subterranean collapse) and, by extension, for longer periods (glaciation, floodplain formation, karst development, coastal evolution). To bring these strands of argument together, however, it is necessary for geomorphologists to recognize geologic inheritance (passive structures, outcrop patterns), and intervention (seismicity, volcanism) and the impacts of global climate change (weathering, desertification), as fundamental inputs to geomorphic reasoning and diversity (Figure 2). In reality this is no more than an elaboration of the traditional view of landforms as products of structure, process and time.

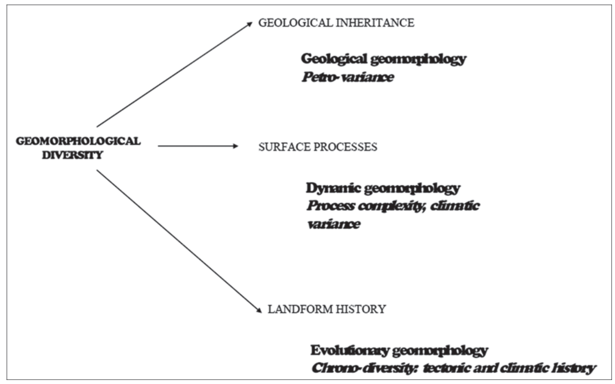


Figure 2 - The components of geomorphological diversity.

Geomorphic diversity as a function of *landscape sensitivity*

The reasons why the Earth's surface does not adopt or conform to the relatively simple surface forming the geoid, are well understood, principally in terms of geothermal heat flows, gravity anomalies and plate tectonics. Uplifted portions of the Earth's crust are dissected by ice and water flows, capable of cutting through resistant rocks and major structures. Yet much of the geomorphic diversity evident in the World's landscapes is due to more subtle and detailed responses to the processes of denudation. Partly this is caused by the concentration of erosion along linear pathways. Denudation rates are, therefore, influenced by proximity to river channels, glaciers and coastlines, and the steep slopes generated by linear erosion. The intensity of surface processes also varies across many orders of magnitude: according to climatic zone, season and the incidence of extreme events.

Much of the diversity expressed in some of the most striking landforms and landform landscapes derives from variation in *landscape sensitivity,* which results in different rates of denudation. The concept of landscape sensitivity derives from the ideas of dynamic or process geomorphology, and expresses the stability or instability of process systems in response to changes in external forcing (see D. THOMAS & ALLISON, 1993; PHILLIPS, 1999; M. THOMAS, 2001, for detailed discussion). To the extent that these process systems support or destroy specific elements of the physiographic landscape, they become the agents of change that lead to increasing heterogeneity in the visible landform. Such morphological expressions of system changes can be transient in highly sensitive and rapidly changing systems, such as bars in a river channel or cuspate forms on a beach, but they can also be persistent: when bars become abandoned and form terraces as stream channels are lowered. *Geomorphic diversity* results from *divergence*, usually over long time periods, of different elements in the landscape. This has always been discussed in geological contexts as *differential erosion*, but in geomorphological research, focused primarily on system properties and changes, the parallels with geological differentiation of landscapes are often overlooked. Crickmay (1974, 1975) expressed this principle in terms of his „hypothesis of unequal activity, as a riposte to the cyclical schemes of Davis and Penck. Geomorphologists have also acknowledged the possibility of *convergence* (PHILLIPS, 1999), and *equifinality* (BERTALANFFY, 1968) amongst landforms, whereby different processes or sequences of processes can result in similar forms. This concept is usually passed over *passim* in general introductions to geomorphology, but in studies of system dynamics, equifinality has many important applications, as in the estimation of regional carbon dynamics in biogeochemical systems (TANG & ZHUANG, 2008).

Although such a discussion does not arise from *chaos theory* (LORENZ, 1963) this field of study envisages a divergence within dynamical systems due to small differences in initial conditions. Chaos theory has been applied to many different dynamical systems, but is characteristically applied to fluid dynamics, and especially to weather and climate. The idea that differences in initial conditions can lead to exponential growth of perturbations (the 'butterfly effect') probably cannot be applied directly to the development of geomorphic diversity, but the underlying concepts are relevant. This is because small differences in initial conditions can become amplified with time and this leads to divergence. Thus if two contiguous locations (A and B), experience divergent rates of chemical weathering and mechanical erosion, they will undergo differential rates of lowering. This leads to altitudinal divergence (increasing relief) between the two locations. Assuming connectivity between A and B the denudation system will experience either positive feedback, leading to accelerated change and divergence, or negative feedback, leading to declining rates of change, and possibly to convergence. In practice, external factors controlling the system: the elevation (tectonic) and/or the water throughput (climatic) are liable to change, and other factors such as ground cover can affect rates of change. Differential lowering will lead to inheritance of features that persist (changing very slowly) over time alongside forms that evolve more rapidly. On the other hand sedimentation can lead to burial or overprinting of surfaces that have survived without major change, and this leads to accumulative sequences that contain a partial history of the landscape (THOMAS, 2001).

Global and local geodiversity

Most of this discussion focuses on geodiversity at the landscape scale: a geodiverse landscape being one that contains highly differentiated forms and materials (rocks and deposits). This implies differentiation by age, origin (process) and morphological expression. Sediments in a basin-and-range landscape from southern Morocco (Figure 3) illustrate these principles and the Geomorphic diversity can be seen to derive from inheritance and processes leading to the basin-and-range topography (Palaeozoic-Cenozoic); terraces with calcrete dating to the Quaternary, and channel floor sands and gravels of variable age, but recording individual events.

There are also many examples of landscapes with high *physiographic* diversity that have arisen from the operation of a single dominant process and/or contain a restricted range of related materials. Examples would include: dune systems/sands; karst systems/limestones; riverine systems/fluvial deposits. How these are viewed in terms of geodiversity then becomes a matter of scale, and also of connectivity or *coupling*, especially as between hillslopes and channels in fluvial systems (HARVEY, 2002; CHIVERRELL *et al*., 2009). In the example above (Figure 3) there is only limited coupling between the mountain range (source of coarse debris and dissolved salts) and the adjacent valley floor (accumulation of slope deposits and precipitation of CaCO3 as calcrete) in terms of process. The channel sands and gravels are derived from a hilly catchment far upstream. But the major sets of forms and materials (hillslope, terrace, channel) contain materials of different age and provenance which contribute to the geomorphological diversity. This fundamental source of diversity dominates the *visual* experience, which derives from the juxtaposition of mountain, terrace and plain.

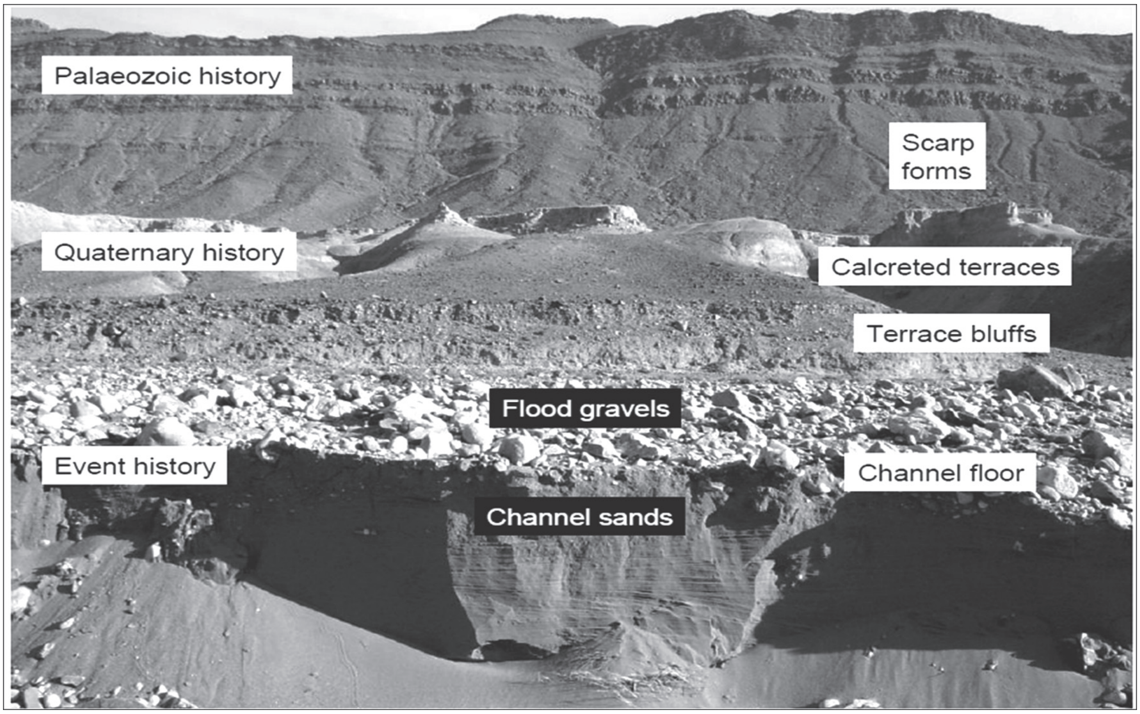


Figure 3 - Generations of geomorphic forms, illustrating sources of geomorphic diversity at the landscape scale, from the Anti-Atlas of southern Morocco (Photo by M. Thomas, 2004).

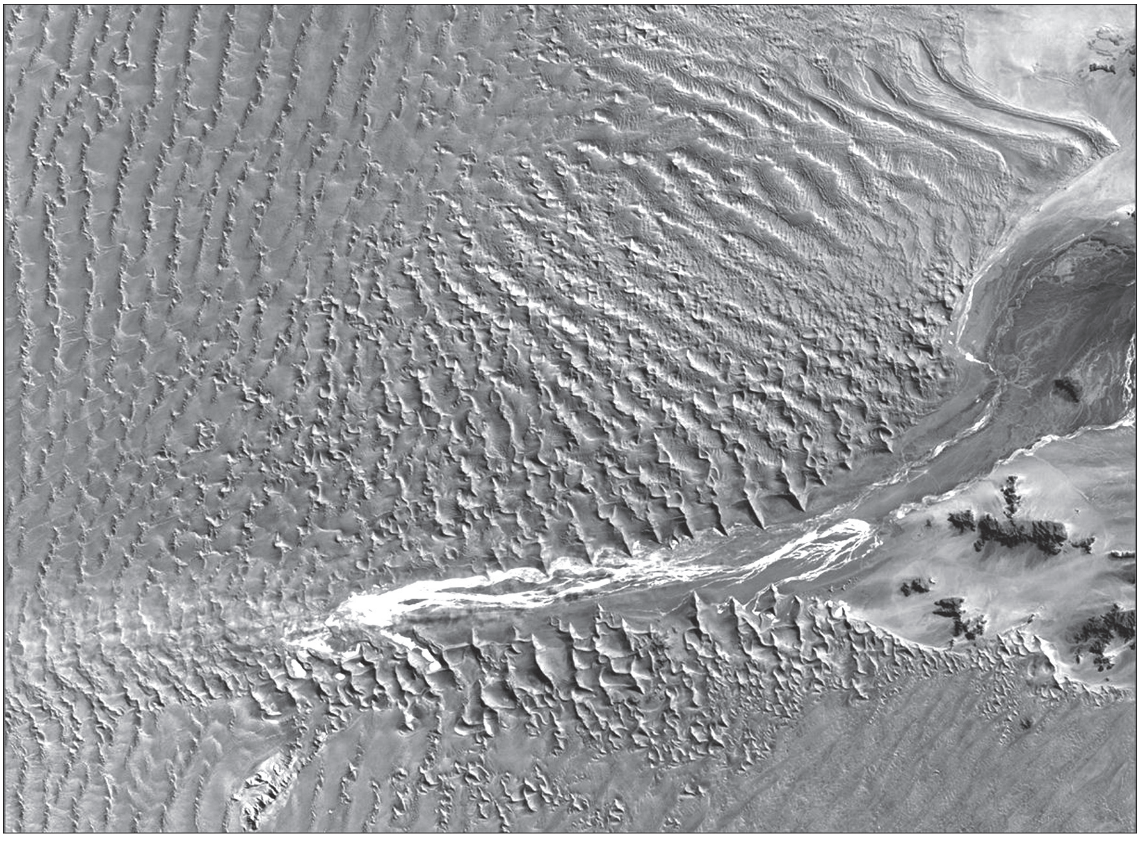


Figure 4 - Dunes of the Namib Desert, also showing the pathway of ephemeral water flows (photo from USGS/NASA).

Figure 5 - View across the Sossusvlei (ephemeral watercourse) to the dunes of the Namib Desert (photo M. Thomas, 2007).

The great sand sea of the Namib Desert (Figure 4) has a major place in geodiversity at a global scale, yet it could be claimed that internal or landscape diversity is limited. Parabolic dune forms dominate large areas, and both geo- and bio-diversity are only increased by the intrusion of water flows (and by some rock outcrops) (Figure 5). The harmonious connectivity between the sand faces in equilibrium with the wind systems, combined with the sparse vegetation along ephemeral watercourses creates a striking landscape with rare and highly prized aesthetic value. It is less clear that, as a landscape, the Namib has an *internal* geomorphological diversity that equals the example from Morocco.

Rather similar arguments can be employed for some hard-rock terrains, in granite or limestone for example, where a few major rock landforms are repeated with great visual impact. The granite landforms in the Mountain Sanqingshan National Park (Figure 6), situated in the sub-tropical monsoon forests of south-central China are both striking in the local context, and also rare in terms of the global geodiversity of granite landscapes. In this area a limited range of granites has been subject to repeated compressional uplift along a suture zone between two lithospheric plates (YIN GUOSHENG, 2006; THOMAS, 2010). The granite massif is crossed by three intersecting fracture sets and is subdivided into closely spaced vertical blocks that have become exposed and eroded into ‘peak forests’ (term used by Yin Guosheng, 2006) (Figure 6). This outstanding and unusual landscape was recognized by UNESCO as a World Heritage Area in 2008.

In many instances of rarity in global geodiversity, a single landform may carry iconic significance: the Half Dome at Yosemite, USA and the Sugar Loaf at Rio de Janeiro, Brazil are examples in granite-gneiss terrain: one glaciated, the other not. This problem, of the ‘unique’ landform has arisen persistently in earlier attempts to characterize scenic quality using numerical indices. More recent concerns with geodiversity come up against the same difficulty: that value is placed on visual expression in the landscape, and this can attach to singular features as much as to regional terrain. It should be emphasized, however, that neither the Half Dome at Yosemite, nor the Sugar Loaf at Rio de Janeiro is an isolated feature, both occur within regional landscapes that contain other, often equally commanding landforms (across the central core of the Sierra Nevada, California, and within the Serra do Mar ranges that extend for 1,500 km along the Atlantic margin of Brazil).

Figure 6 - Granite pillars (called 'peak forests' by Yin Guosheng, 2006) in the Mountain Sanqingshan National Park, P.R.C. (inscribed as a World Heritage Area by UNESCO, 2008 (Photo by M.Thomas, 2007).

Landform divergence and geodiversity

The sources of geomorphic diversity are found in the differential rates of both magmatic and surface processes, and in unique combinations of many different processes, operating both concurrently and sequentially over widely different time periods (Figure 7).

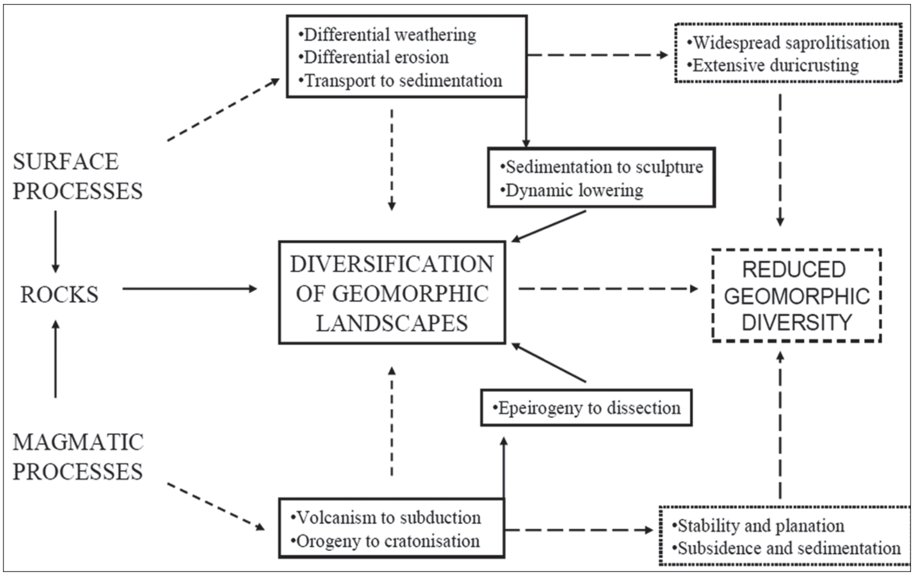
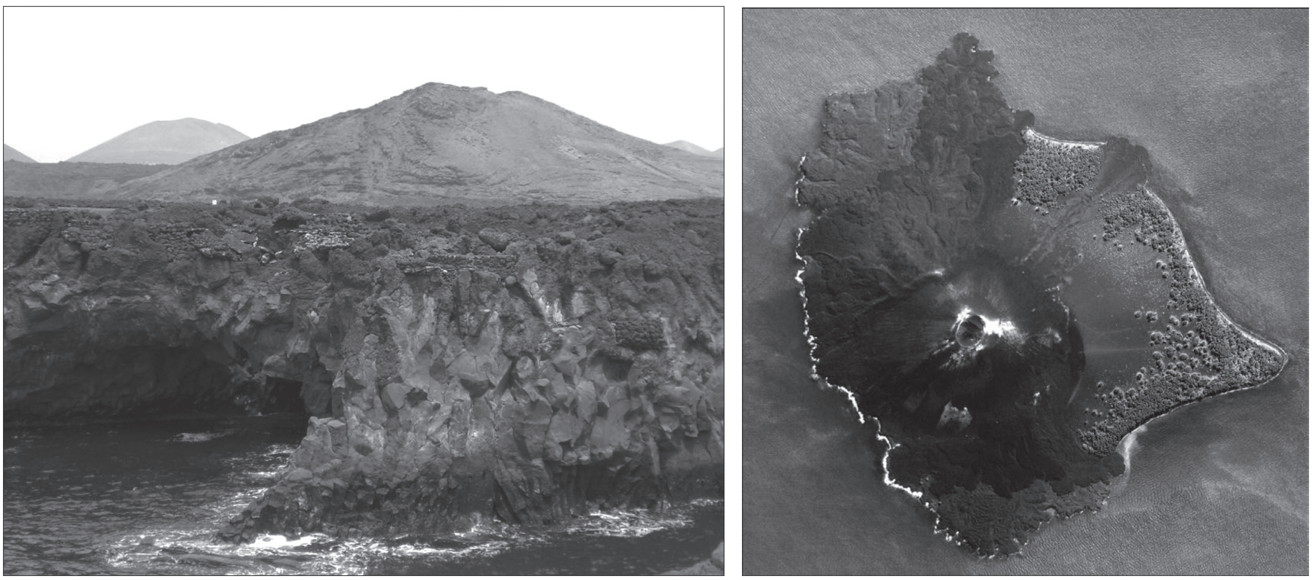


Figure 7 - Process interactions leading to diversification of geomorphic landscapes and also to reduced diversity. To preserve clarity time periods are not specified, but all processes can act on different temporal and spatial scales.

Recent volcanism and geodiversity

It is possible to argue that geodiversity actually increases with landscape ‘age’, and that only subduction or total dissolution of rocks can eliminate inherited forms and materials to restart the process of diversification. But this argument comes up against some serious objections. In the case of newly-formed volcanic landscapes high physiographic diversity is evident, even though the ages and range of rock types may be restricted, and biodiversity may be low. The Timanfaya National Park, in Lanzarote (Islas Canarias, Spain, 28ºLat.N) (Figure 8a) illustrates this point. Explosive eruptions took place from 1730-1736, creating a new landscape of ash and cinder cones, and some important lava flows, diversified by tunnels. The low rainfall (<200 mm pa) has inhibited soil development and plant migration and, although some rare plants are found, biodiversity is low. More favourable conditions for the development of biodiversity in similar circumstances are exemplified by Anak Krakatau (Indonesia, 6ºlat.S), which was formed by renewed eruptions between 1927 and 1930, 47 years after the destruction of the island of Krakatau by an explosive eruption in 1883. But despite high, equatorial rainfall a soil cover has yet to form, and seeding of plants has been restricted to coastal areas with on-shore winds while later eruptions have also disrupted the developing vegetation (Figure 8b). Wilson (1992) celebrated the resilience of life forms by reference to Anak Krakatau, noting its forested aspect when viewed from the sea. The satellite image (Figure 8b), however, demonstrates the limited extent of the plant cover and how the increasing geodiversity, which has resulted from the repeated volcanism has also limited the development of biodiversity on the island.



A **B**

Figure 8 - A. View of Timanfaya National Park, Lanzarote, Islas Canarias, Spain. The northwestern corner of the island experienced catastrophic volcanism between 1730-1736, creating a scenically diverse landscape from lavas and ashes. The development of biodiversity has been limited by the low rainfall (<200 mm p.a.). Most landforms are constructional and sea caves are mostly lava tunnels. Photo by M. Thomas, 2008. B. Aerial view of Anak Krakatau a volcanic cone formed within the sunken caldera of the island of Krakatau, destroyed in 1883. Plant seeds have arrived by sea from neighbouring islands and the spread of vegetation is taking place from the coast. Photo by NASA, USA, 2009.

On older landscapes, particularly in humid tropical and sub-tropical areas the processes of chemical (and biochemical) weathering have led to the formation of widespread, deep saprolite. Early geomorphologists, including Davis, thought that the weathered mantle would develop as a blanket on peneplains of subdued relief. But, although ancient surfaces of planation may be associated with extensive weathering, the processes of chemical decay are accelerated by deep penetration and rapid throughput of groundwater. This occurs in elevated areas that have become dissected by rivers, and is favoured by rock fractures and the weakening of rock fabric by tectonic stresses. In these circumstances differential rock decay becomes the decisive process by which differential denudation and geomorphic diversity develop. But in areas of subdued relief, the formation of a weathering mantle (saprolitisation) and extensive duricrust (usually calcrete or ferricrete) can reduce geodiversity (Figure 7). Not only does relief become subdued but rock outcrops can be infrequent.

At the regional scale geomorphological diversity can reflect both regional planation with extensive residual deposits, and the differentiation of relief according to rock resistance to chemical decay. In West Africa, the Leo Uplift has elevated the watershed zone between Atlantic and Niger drainages during the early Mesozoic break-up of Gondwana. Subsequent erosion has deposited terrigenous sediment in interior basins to produce extensive plains with low physiographic diversity. The steeper slope towards the Atlantic Gulf of Guinea coast has led to dissection, and there is often an intimate relationship between the relief forms and geology, mediated principally by chemical weathering processes (see THOMAS, 1994). Long-continued dynamic lowering of the landscape, leading to divergence according to rock resistance was a central concept developed by Hack (1975, 1979), who demonstrated that quite small differences in lithology could lead to divergent hillslopes. He cited the role of chert in saprolite, supporting slopes in temperate limestone areas. In the humid tropics this role is most commonly exercised by ferricrete duricrusts, while calcrete is effective in sealing and stabilizing landsurfaces in semi-arid, sub-tropical areas (STOKES *et al*., 2007).

Geomorphic diversity in Guinea

In Guinea, West Africa (9ºN Lat.) Proterozoic sandstones form the Futa Djalon Mountains and overlie an Archaean basement of crystalline rocks along the crest of the Leo Uplift. There is a wet savanna climate with high rainfall (P = ca. 2,500 p.a.) but also an intense dry season of 5 months duration (Figure 9 A, B). In this area the impact of deep chemical weathering on the crystalline, basement rocks has dominated the formation of the landscape, while the sandstones, although capped by bauxites, have remained essentially unaltered (CHARDON *et al*, 2006). Sandstone plateau remnants bounded by steep escarpments give way to multi-convex topography, where the sandstones have been stripped from the underlying crystalline basement. East of this boundary, close to the Atlantic-Niger watershed, the convex hills become more subdued, or are replaced by *koppies* (tors) (Figure 10 A), and shallow slopes intervene between the residual hills and swampy water courses. In some catchments underlain by mafic rocks, the wet-season flux of reduced Fe compounds is followed by dry-season oxidation and precipitation of Fe as hematite and goethite, gradually forming extensive duricrusts, which have created subdued local landscapes known as 'bowé' (from the Foula word *bowal* (MAIGNIEN, 1958) (Figure 10 B). In the absence of rapid denudation, weathering processes thus tend to decrease geodiversity by obscuring rock outcrops and diminishing rock landforms. This process begins even along the escarpment zone in West Africa, where mass movement of regolith has been arrested by ferricrete formation even on quite steep slopes.

A

B

Figure 9 - A –upper. Massive sandstone escarpment of the Futa Djalon Mountains, Guinea, West Africa. B –lower. Steep multi-convex relief in weathered granitoid rocks in the same area. Photos by M.Thomas, 2008.

A

B

Figure 10 - A – upper. Residual rock cores (tor, koppie) as an intermediate product of granite weathering. B –lower. 'Bowe' landscape with extensive duricrust (ferricrete), effectively sealing the land-surface of a small valley. Both photos from Guinea, West Afica. Photos by M. Thomas, 2008.

Weathering and geomorphic diversity in equatorial Kalimantan

The efficacy of chemical weathering in defining landscape character is further illustrated by the landscapes of NW Kalimantan, Indonesia. This areas lies astride the Equator and receives 2000-4000 mm rain per annum with only short dry periods. In this area, Mesozoic sediments provide a sedimentary basement into which mid Miocene and later epithermal igneous rocks have been intruded. Some prominent hills stand above an undulating, multi-convex topography, and the igneous rocks (often granodiorite) are deeply weathered to form alumina-rich saprolite (bauxite) (Figure 11 A). Over sandstones and the sandy deposits in coastal valleys and lowlands distinctive "white sands" have become leached of all mobile constituents. Pedologically these are giant tropical podzols which lack clay and support a species-poor *kerangas* heath forest (Figure 11 A, B) (THOMAS *et al*., 1999). Both biodiversity and geodiversity are low in these areas, and the soils supporting the *kerangas* have little productive potential (PROCTOR, 1999). But the heath forests are rare on a global scale and there is concern for their conservation.

A **B**

Figure 11 - A. Aluminous saprolite with gibbsite nodules, NW Kalimantan, Indonesia. Photo by M. Thomas, 1997. B. White sands exposed by gold mining in NW Kalimantan, Indonesia. Photos by M. Thomas, 1997.

These few examples illustrate the role of chemical weathering in creating and masking geodiversity under humid tropical conditions. Over wide areas fresh rock outcrops can be rare, and are found mainly along permanent stream courses. This can pose problems for engineers, and also makes it difficult to find fossil localities.

Plate tectonics and climatic divergence

At the global level a great deal of geodiversity has its origins in climate history, which has been influenced by plate tectonic movement. In the first place the former Gondwanaland continents have come to occupy the tropical latitudes and to dominate them in terms of area. This is illustrated in Figure 12, from the Eocene Epoch. The generally northerly movement of the plates has been highly differential from a former grouping around the South Pole in the Jurassic.

While South America moved northward slowly and straddles the Equator throughout, Africa shifted faster, taking the interior of NW Africa into arid latitudes and the northern Kalahari into the humid tropics (ancient sand sheets are found in Angola). India moved more rapidly across the Equator taking northern areas into drier climates, and leaving the southern tip (Kerala and Tamilnadu) in the humid tropics. Australia's detachment from Antarctica was delayed and the continent did not approach the tropics until the mid Miocene, its present position being dominated by trade-wind aridity, with only the northeastern fringes experiencing humid tropical conditions.

This well known scenario has led to profound differences in landforms and residual deposits between the continents (TARDY & ROQUIN, 1998). The generally warm and moist conditions that prevailed during the Cretaceous and early Cenozoic changed progressively towards differentiated regional climates, each with steep temperature and moisture gradients. With the growth of the Antarctic ice sheet rapid climatic changes towards cooler and drier conditions occurred across southern latitudes in the mid Miocene. In the Quaternary profound changes to global climates imposed further perturbations, some of them highly localized.

A consequence of these changes, especially during the last 100 MA, has been an ever increasing geomorphic diversity in areas experiencing dissection. Many such areas are passive marginal terrains, where the dismantling of ancient planation surfaces and their underlying residual deposits has also led to geochemically-based differential denudation and increasing local relief (THOMAS, 1989, Part II; TWIDALE, 1991). A sensitive adjustment of landform to rock mineralogy, fabric and structure has developed in these areas, as noted above and in the work of Hack (1975, 1979). In folded terrain, faults zones and rifts, and in volcanic provinces, other models are needed, though structure is often a determining factor and explanations often lie in global convective systems (plumes, “hotspots”) and plate tectonic movement (from collision tectonics to formation of rifts at divergent plate boundaries).

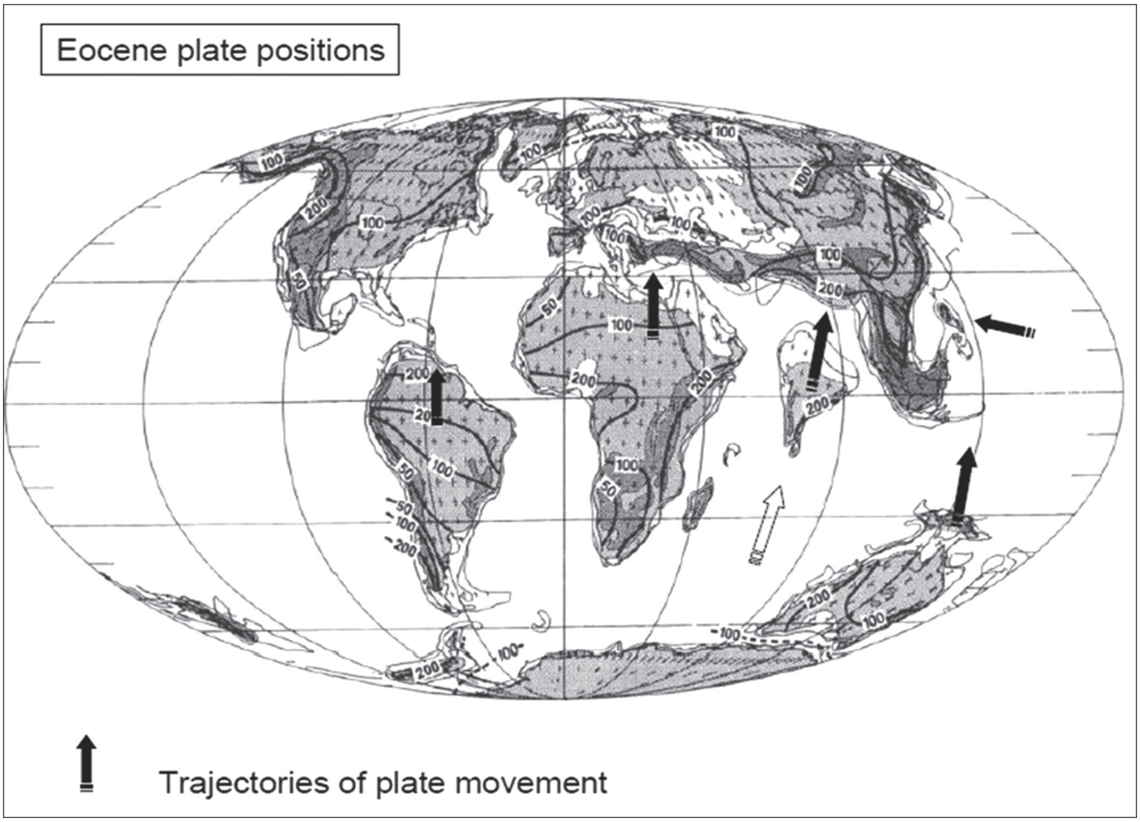


Figure 12 - Continental plate positions and precipitation patterns in the Eocene. Precipitation figures are approximate and in cm.

Summary and conclusions

Geomorphic diversity, therefore, needs to refer to both spatial and temporal sequences and the origins of diversity must be sought in both the nature of geologic substrate and the complex processes that operate on these materials through time. Ruxton (1968) wrote about “order and disorder” in landform, and attributed the latter to *multicomplexity of process* and to *inheritance*, and this observation contains essential keys to understanding geomorphic diversity at the landscape scale.

Petro-variance (BÜDEL, 1968), is one aspect of the geological inheritance that for some is the dominant reason for all geodiversity. But the history of geomorphology has reflected a tension between the role of geology, the influence of process and the importance of the evolutionary timescale (GERRARD, 2008). Arguments around the begining of the 20th Century often hinged on the idea of a “cycle of erosion” operating across rocks and structures, a few ‘monadnocks’ only rising above the resulting peneplain (DAVIS, 1899,a,b). Others, such as Gilbert (1877), sought explanations in the energetics of the landsurface. Climatic (and *climatogenetic*- BÜDEL, 1968) geomorphology flourished, especially in Germany, and a rather sterile debate about climatic geomorphology ensued in anglophone literature (STODDART, 1969). Sub-division of the Earth according to climatic zones, for the characterization of geomorphic landscapes has continued (GUTIÉRREZ ELORZA, 2001, eg), and includes some books designed for practical use, by engineers for example (FOOKES *et al*, 2005). This is also a complex field of enquiry, because, as Büdel (1968) recognized the distribution of global climates has shifted radically during the Phanerozoic, so that imprints of past climates are found alongside the products of recent floods and landslides.

For all these reasons geomorphic diversity, as a phenomenon is highly complex and attempts at numerical indices of diversity have to compete with subjective and also aesthetic judgements about the value of iconic, possibly unique, landforms and landscapes. From a theoretical viewpoint Phillips' discussion of the ‘perfect landscape’ (PHILLIPS, 2007) conceptualizes this issue, while others have pursued a pragmatic course to provide a ‘geodiversity index’ (SERRA-

NO CAÑADAS & RUIZ FLAÑO, 2007). Modeling based on digital terrain models (DTMs) and using artificial neural networks has been proposed by Eshani & Quiel (2008) for the parameterization of relief, but this study was not specifically targeted at the definition of geomorphological diversity.

This discussion does not seek to define indices for geomorphological diversity, and does not criticize attempts to provide these for practical purposes. There is a danger, however, that purely quantitative approaches to this issue may fail to recognize what is important and, therefore, why particular features or landscapes need protection or should be conserved. Even the notion that a high index of geodiversity must always indicate valuation higher than that accorded to isolated or repetitive forms remains problematic, and is subject to considerations of scale. Thus on a global scale coral atolls are restricted in climatic range and geotectonic setting but, individually, they may be rather simple geomorphic systems. Volcanic or continental islands with barrier reefs will have greater geodiversity. Each will have different sensitivities to change (atolls to sea-level change; volcanic islands to renewed eruptions and possible subsidence). It also follows that the Great Barrier Reef bordering the northeastern coast of the continent of Australia is unique, when considered as a single entity, but it also contains a myriad barrier reefs and islands. It challenges our sense of scale in this type of enquiry.

The following points can be made in summary:

1. The sources of geomorphological (geomorphic) diversity are complex and reflect the operation of process systems over all timescales.

2. The recognition of geomorphic diversity is dependent on the spatial scale of enquiry.

3. Although many landscapes appear to have increased in complexity through time due to the divergence of landform elements in response to the operation of earth surface processes, this is not an 'aim' within the geomorphic system and the trend toward increasing complexity can be reversed.

4. Reduction in complexity or diversity can arise from the elimination of relief (planation), saprolitisation, subsidence and burial by sediment, and by volcanic eruption.

5. Rare landforms are recognized for their individuality and such features arise in many contexts. They are often single mountains (Uluru/Ayer's Rock, Mount Vesuvius, egs.) but are more often singular features within wider geomorphic/ geologic systems.

6. At a regional scale harmonious juxtaposition of many similar landforms can create highly distinctive and appealing landscapes (the 'peak forests' of Sanqingshan, and tower karst of Guilin in China; the domes and boulders of the Matopos Hills, Zimbabwe and the sandstone pseudo-karst of the Bungle Bungle, Australia, are examples).

7. On the single criterion of diversity, landscapes with internal contrasts would always be valued higher (peaks, alpine benches and valley floors in glaciated mountains; sandstone towers – *tepuis* – amongst basement outcrops and domes; some great escarpments such as the Drakensberg, South Africa).

8. In tropical and sub-tropical, humid landscapes the role of chemical weathering in developing geomorphological diversity is of central importance. This is because both the surviving, residual forms and the re-deposited products of weathering are due to and shaped by these processes.

9. The long-continued modification of terrain by chemical processes can eliminate diversity, as weathered residuals become destroyed and some rocks are completely dissolved. In these cases the penultimate products of rock destruction (duricrusts, sand sheets) can be considered to have importance in wider discussions of both biodiversity and geodiversity.

10. Links between biodiversity and geodiversity exist but the terms remain conceptually and theoretically distinct. At the landscape scale, however, a geodiverse terrain with varied elevation, slope, aspect, and materials with different hydrodynamic properties, will provide a wide range of habitat niches which will promote biodiversity.

11. In some geomorphic environments, notably those affected by repeated volcanism, or extensive valley-floor flooding, developing biodiversity can be eliminated from areas affected, while the geodiversity increases with each episode.

12. Finally, it is possible to challenge the assumption that high levels of biodiversity and geodiversity somehow imply more stable or more balanced systems, and the conservation of particular species or specific geomorphic features may require greater emphasis.

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Author:
Michael F. Thomas, School of Biological and Environmental Sciences, University of Stirling,
Stirling, FK9 4LA, // Scotland, United Kingdom. E-mail: m.f.thomas@stir.ac.uk