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# Landforms of the Earth

## An Illustrated Guide

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*Nieves, Marina, Isabel and Francho*

# Preface

This book has been produced by two university lecturers with long experience in teaching geomorphology and other related subjects. Students enrolled in courses dealing with earth-surface processes and landforms (geomorphology, physical geography, geology, geohazards, environmental sciences) have access to excellent geomorphology textbooks with superb descriptions. However, only some of the landforms explained in those publications are illustrated with images. This hinders the comprehension of explanations on the landforms and genetic processes and the students' capability to correctly diagnose geomorphic features, both in the field and using remote-sensed data. We feel that visualization of landforms is essential for learning geomorphology and stimulating the interest on this field-based subject; a picture is worth a thousand words.

Nowadays, researchers dealing with geomorphological issues are overwhelmed by an enormous variety of rapidly evolving techniques. Some of them, like dating methods, remote-sensing, or geographical information systems, have greatly contributed to the recent renewed interest in geomorphology. However, the means should not set aside the aims. Basic knowledge is essential to conduct compelling geomorphological investigations, regardless of the sophistication of the methods used. We may use the best available remote-sensed data, but we only see what we know. Remote-sensed data may provide a great deal of information on the landforms, but we should feel forced to examine them directly in the field. The new techniques can complement the classical field-based approaches, but cannot replace most of them.

We hope this photographic guide will constitute an useful educational resource for students, researchers, and practitioners. It may also satisfy the curiosity of people keen on nature, travellers and landscape photographers, who want to learn about the names and origin of the landforms they encounter in their trips. Commonly, stunning geomorphological features constitute the main highlight of protected areas (National Parks, UNESCO World Heritage Sites) and outstanding tourist attractions.

The book illustrates with more than 360 photographs and satellite images from all over the world the main landforms of the Earth's continental surface. The good quality colour images have been thoroughly selected, showing representative and dramatic examples. Each landform or group of geomorphic features is described with concise, direct, and easy-to-read texts. The structure of the book follows classical subdivisions of geomorphology, with five chapters dealing with structural geomorphology (structural, tectonic, volcanic, karst, and granite landforms), four devoted to azonal geomorphic systems and processes (weathering, slope movements, fluvial, and coastal landforms), and three chapters covering the three main morphoclimatic environments (glacial, periglacial, and desert-aeolian landforms). Readers can easily find more lengthy and in-depth explanations in the general and specific geomorphology textbooks recommended at the end of the book.

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# Contents

# 1 Introduction

Geomorphology literally means the study of the Earth's landforms. It is defined by the International Association of Geomorphologists (IAG; www.geomorph.org) as the interdisciplinary and systematic study of landforms and their landscapes, as well as the Earth surface processes that create them. Geomorphologists investigate landforms and landscapes addressing multiple aspects, such as their genesis, morphometry, chronology and past and future evolution. They also investigate Earth surface processes not only to understand their morphogenetic role, but also to gain a scientific basis for assessing and managing a great deal of environmental problems associated with them, notably geohazards (e.g. landslides, floods, subsidence, earthquakes).

The concept of geomorphology has rapidly evolved over its short history. During its initial stages, the pioneers of the discipline were mainly interested on the reconstruction of the long-term evolution of present-day landscapes (historical geomorphology). That was a period during which geoscientists were largely focused on obtaining information about the past. This retrospective approach was commonly based on the application of the uniformitarianism principle: "the present is the key to the past". In a subsequent phase, qualitative descriptions were replaced by quantitative studies on both processes and landforms, largely thanks to the development of new technologies. Measuring the dimensions of landforms (morphometry), analysing their spatial distribution and frequency and quantifying rates of processes and the associated morphological changes are some of the main targets of quantitative geomorphology. Both historical and quantitative investigations have benefited by the advent of new dating techniques that allow determining the age of landforms and deposits and calculating temporal frequencies and rates; no dates no rates. Recently, there has been a significant trend to applying geomorphology as a tool for assessing and mitigating environmental problems like hazards and impacts (applied or environmental geomorphology). Nowadays, a major challenge is the development of reliable predictions on the future behaviour of Earth surface processes and landforms. This prospective approach is usually developed by using the present and the past as the key to the future, through a reverse uniformitarianism concept. Modern geomorphologists are more worried about the surface processes that operate today and those that will have consequences tomorrow, because they affect our society. This concern is largely motivated by three factors: (1) Damage related to various hazardous geomorphological processes (e.g. floods, landslides) is increasing exponentially. (2) Humans are currently one of the main geomorphic agents by causing direct changes on the land surface or by producing disturbances that significantly change the dynamics of geomorphic systems. From 1900 AD to 2000 AD, the world population increased fourfold to almost six billion people, and economic activity increased 40-fold. In fact, a new geological epoch called the Anthropocene has been proposed, covering the period during which human activities have had a profound imprint on the Earth's landscapes and ecosystems. (3) There is a need to forecast the numerous impacts of the anthropogenic global warming on geomorphic systems, some of which will have significant detrimental effects for our society (e.g. sea-level rise). The current boom of geomorphology is most probably due to its social relevance.

Landscapes are the result of the competing effects of endogenous processes, like tectonic activity and volcanism that create topography, and exogenous processes that tend to erode upland regions and accumulate sediments in lowlands and subsiding areas. The distribution and configuration of the large morphostructural units of the planet are largely governed by plate tectonics (megageomorphology). A small fraction of the energy involved in the horizontal translation of the lithospheric plates is converted into the work necessary to uplift rocks against gravity. Solar energy is the main engine for Earth surface processes. It evaporates water and raises moist air in the atmosphere. The vapour condenses at high elevation and falls as precipitation. The potential energy of the meteoric water is transformed into kinetic energy and expended by doing geomorphic work, including erosion and transport of sediments.

Surface processes, controlled by a number of extrinsic and intrinsic factors, may create and modify landforms.

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Some changes in the landforms are related to processes or stimuli that exceed a critical threshold (e.g. landslide triggered by earthquake shaking). Those adjustments may be immediate or can be achieved over a certain period, called the response time (e.g. isostatic rebound related to deglaciation). The magnitude and frequency patterns of morphogenetic processes are highly variable (gradualism versus catastrophism). Some processes produce continuous gradual changes (e.g. dissolution in a phreatic conduit), others occur sporadically and catastrophically (e.g. volcanic explosive activity) and others have a mixed behaviour, with long low-intensity periods punctuated by discrete extreme events (e.g. the flow in a river). The resulting landforms have highly variable persistence times. Some geomorphic features are ephemeral (e.g. small sand dunes), whereas others have a high preservation potential (e.g. glacial cirques).

Landforms can be created by the accumulation of sediments (depositional landforms) or sculpted on pre-existing material (erosional landforms). The genetic interpretation of some landforms may be complicated by morphologic convergence or equifinality, whereby different processes produce very similar features (e.g. fault scarps generated by large gravitational mass movements and tectonic faults). Relict or inherited landforms are those that formed in the past under environmental conditions different than the present-day ones (e.g. an ice-free glacial trough). These geomorphic features can be used to infer paleoenvironmental information and reconstruct the evolution of the landscape. The relative chronology of landform assemblages can be resolved on the basis of spatial relationships (e.g. cross-cutting, inset or superposition relationships) and other attributes, like the degree of degradation and weathering or the maturity of the soils developed on them. These chronological schemes can be significantly improved in some cases utilising geochronological methods.

The structure of the book follows classical subdivisions of geomorphology. The broad field of structural geomorphology, which deals with landforms generated by endogenous processes (active tectonics, volcanism) or controlled by lithological and structural factors, is addressed in five initial chapters. Structural landforms (Chap. 2) are mainly erosional features controlled by the geological structure and the distribution of rocks with different degrees of resistance. Tectonic landforms (Chap. 3) are those created by surface deformation related to active tectonic structures. Volcanic landforms (Chap. 4) include those generated by active volcanism and hydrothermal activity, as well as specific erosional features developed on volcanic rocks. Karst landforms (Chap. 5) occur on soluble rocks and are mainly created by dissolution and precipitation. Granite landforms (Chap. 6) are the geomorphic features that are typically formed on granitic rocks.

A second group of four chapters illustrate landforms associated with widespread geomorphic systems found in most morphoclimatic regions and geological contexts (azonal geomorphology). Weathering landforms (Chap. 7) are related to the breakdown and decomposition of materials at or near the surface by physical, chemical and biological processes. Slope movements (Chap. 8) involve the gravitational displacement of slope-forming materials. Fluvial landforms (Chap. 9) are erosional and depositional features generated by running water, mainly rivers. Coastal landforms (Chap. 10) occur where the land and the sea interact, and waves, tides and nearshore currents play a major role.

The last part of the book comprises three chapters that cover the landforms typically found in specific morphoclimatic regions (climatic geomorphology). Glacial landforms (Chap. 11) are formed by glaciers in cold regions. Periglacial landforms (Chap. 12) are associated with cold non-glacial regions characterised by intense freezing and thawing activity and perennially or seasonally frozen ground. Desert and eolian landforms (Chap. 13) occur in warm arid regions with limited precipitation and scarce vegetation cover.

# Structural Landforms

# 2

Structural landforms are geomorphic features controlled by the underlying geological structure and the distribution of rocks with different resistances to erosion. Erosion tends to preferentially exploit zones underlain by weaker rocks (differential erosion), generating an uneven topography controlled by litho-structural factors. Spatial variations in bedrock erodibility may be related to a number of mappable lithological and structural features. In stratigraphic successions, lithological changes may be related to the superposition of different rock units through conformable or unconformable stratigraphic contacts or to lateral facies changes. Faults (normal, reverse, strike-slip and oblique) may control selective erosion in two main ways. The shattered and sheared material associated with fault planes and fault zones are typically weaker. Faults may also juxtapose different rock units with markedly different resistances to erosion. In areas with plutonic rocks, the lithological changes and their geometrical characteristics may be controlled by the intrusive contact of the igneous bodies with the country rock. The contact may have a dome-shaped geometry (batholiths, laccoliths), a planar subhorizontal shape (sills) or a steep attitude (dykes, volcanic necks).

A major factor controlling the development of erosional landforms in regions underlain by sedimentary successions is the dip of the strata and the distribution of different types of folds (e.g. anticline, syncline, monocline). In these regions, structural surfaces tend to develop on the upper boundary of resistant rock units. These are conformable surfaces in which the topography matches the attitude of the bedding (e.g. flat-topped mesas, dip slopes in cuestas and hogbacks). The orientation and flow direction of drainages with respect to the strike and dip of the strata play an important role in the configuration of these landscapes. In some cases there may be a lack of concordance between the topography and the underlying structure, an example being discordant relief, in which elevated areas occur associated with downthrown fault blocks or synclinal structures consisting of more resistant rocks.

The erodibility of rocks depends on multiple factors in addition to lithology. Fractures and faults are the main mechanical weaknesses in the typically hard igneous rocks. In sedimentary rocks, the main mechanical discontinuities include the bedding planes, joints and faults. The resistance to erosion of the different sedimentary formations is also influenced by other factors including the rock unit thickness, the spacing of the bedding (e.g. massive versus thinly bedded), the presence of interstratified softer beds or the degree of cementation. Some rock types like carbonates, evaporites and granitoid rocks display specific landform assemblages, which are the focus of the chapters on karst and granite landforms.

## 2.1 Mesa and Butte

The main characteristics of the landscape are frequently controlled by the underlying rock units, which may have contrasting resistance to erosion, and their structure (e.g. horizontal, homoclinal, folded, faulted). Fluvial incision into a flat-lying sedimentary succession with alternating soft and resistant units tends to produce a stepped topography with compound slopes. Structural benches and rock scarps (free-face slopes) develop on resistant rocks, whereas the slopes underlain by the more erodible units are gentler and commonly covered by colluvium (debris slopes) (Fig. 2.1A). Dissection in combination with slope recession may result in the development of residuals or outliers called mesas and buttes. Both are flat-topped hills with steep slopes in which an upper resistant caprock protects the underlying softer sediments. The Spanish term mesa, meaning table, is used for relatively large residuals, whereas butte refers to hills with limited areal extent (Figs. 2.1B, 2.1C and 2.1D).

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**Fig. 2.1A** The Colorado River valley at Dead Horse Point, Utah, shows a stepped topography with structural benches and scarps on flat-lying resistant and nonresistant sedimentary rocks (Published with permission of © Francisco Gutiérrez 2015. All Rights Reserved)

**Fig. 2.1B** Flat-topped mesa developed on horizontally lying mudstones capped by a resistant gypsum bed (El Planerón, central sector of the Ebro Cenozoic Basin, NE Spain) (Published with permission of © Francisco Gutiérrez 2015. All Rights Reserved)

**Fig. 2.1C** Butte in Monument Valley, Arizona, consisting of soft sediments (Organ Rock Shale) overlain by resistant scarp-forming rocks, mainly the massive De Chelly Sandstone (Published with permission of © Francisco Gutiérrez 2015. All Rights Reserved)

**Fig. 2.1D** Butte formed by densely gullied Mancos Shale capped by a relatively thin sandstone bed (west of Hanksville, Utah) (Published with permission of © Francisco Gutiérrez 2015. All Rights Reserved)

## 2.2 Cuesta and Hogback

Homoclinal structures are sedimentary successions with a constant dip. Where gently dipping sequences consist of stratigraphic units with contrasting resistance, differential erosion of the softer sediments tends to produce a series of asymmetric valleys and ridges parallel to the structural trend. The ridges show a gentle backslope roughly concordant with the resistant strata (dip slope) called a cuesta, a Spanish word that means slope (Fig. 2.2A). The shorter and steeper opposite slope is carved in soft sediments protected by the resistant caprock. Where the strata have a higher dip, the more symmetric ridges controlled by a resistant unit are called hogbacks (Fig. 2.2B). Different terms are used to describe drainages according to

**Fig. 2.2A** Cuesta topography developed by differential erosion on alternating and gently dipping Jurassic limestone and marl units (contact zone between the Iberian Chain and the Ebro Cenozoic Basin, NE Spain) (Published with permission of © Francisco Gutiérrez 2015. All Rights Reserved)

**Fig. 2.2B** Hogback on the southern flank of the Gavbast anticlinal ridge, developed on marls of the Gachsaran Formation capped by Guri Limestone (Bastak, Zagros Mountains, Iran) (Published with permission of © Francisco Gutiérrez 2015. All Rights Reserved)

their direction with respect to the dipping structure. Consequent, obsequent and subsequent streams indicate drainages flowing in the dip direction, in a direction opposite to the dip and parallel to the strike, respectively. These terms tend to be replaced by the more intuitive and less confusing words dip, antidip and strike drainages, respectively.

## 2.3 Chevron and Flatiron

Incision of dipping and well-bedded stratigraphic sequences by evenly spaced transverse gullies produces a serrated pattern given by the layers with different resistance to erosion and colour, called chevrons. These are V-shaped features with the apexes pointing upslope in the interfluves and downstream in the valleys, in accordance with the "Rule of Vs" (Fig. 2.3A). Differential erosion in the interfluves may individualise resistant beds, forming steeply inclined fin-like facets, known as flatirons (Fig. 2.3B).

## 2.4 Ridge and Rock Wall

Differential erosion in terrains underlain by vertical stratigraphic sequences including rocks with contrasting erodibility commonly results in the formation of ridges along the more resistant beds or formations. These landforms may show a complete morphological gradation, from ridges with a triangular cross profile to tabular walls with a high height-to-width ratio standing up as residuals (Figs. 2.4A and 2.4B). Equivalent landforms develop on vertical dykes where the fracture-controlled igneous intrusive rocks are more resistant than the country rock (Fig. 2.4C). Dykes may form dense swarms with prominent geomorphic expression. They may display parallel, intersecting and radial patterns. The latter generally occur around larger intrusions where the updoming associated with the emplacement of the igneous body produces systems of radial extensional fractures. A less common situation is that of dykes less resistant that the host rock, which favours the

**Fig. 2.3A** Chevrons developed on well-bedded Late Cretaceous limestones and marls, Bea village, Iberian Chain, NE Spain (Published with permission of © Arturo Polo-Ena 2015. All Rights Reserved)

**Fig. 2.3B** Flatirons on steeply dipping red conglomeratic sandstone of the Fountain Formation, Boulder, Colorado. These structural landforms occur on the erosional escarpment developed along the eastern margin of the Colorado Front Range (Published with permission of © Francisco Gutiérrez 2015. All Rights Reserved)

**Fig. 2.4A** Rock walls developed by differential erosion in a formation with vertical attitude consisting of resistant and tabular limestone layers interbedded within softer argillaceous sediments (Finestres, Canelles Reservoir, Spanish Pyrenees) (Published with permission of © Francisco Gutiérrez 2015. All Rights Reserved)

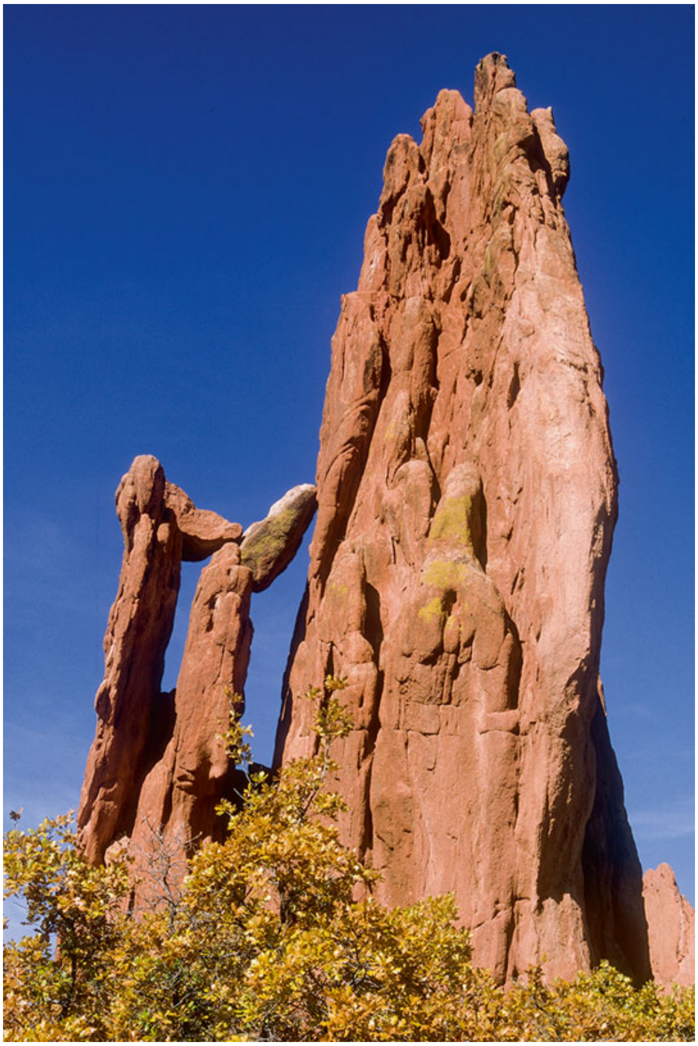

**Fig. 2.4B** Vertical fin-like ridge developed by selective erosion in sandstone beds of the Fountain Formation, Garden of the Gods, Colorado (Published with permission of © Francisco Gutiérrez 2015. All Rights Reserved)

development of erosional troughs and drainages that exploit the softer intrusives.

## 2.5 Monoclinal Scarp

A monocline develops where horizontal or very gently tilted strata bend abruptly along a narrow zone to form a step-like fold. These are asymmetric folds with an upper anticlinal hinge, a middle steep limb and a lower synclinal hinge. They are frequently related to ductile bending of strata above steep blind basement faults (fault-propagation folds) and commonly occur in the marginal sectors of structural uplifts and basins (e.g. Colorado Plateau region). They may also form by passive bending over migrating dissolution fronts in dipping evaporitic formations. These folds control the development of monoclinal scarps whose face corresponds to an abrupt dip slope associated with the forward tilted middle limb. This topography may be related to active monoclinal folding itshelf and/or differential erosion (Fig. 2.5). The crest of monoclinal folds is frequently broken by extensional structures like fissures or crestal grabens.

## 2.6 Anticlinal Ridge

In terrains underlain by folded sedimentary successions, a concordant topography consists of a series of ridges and valleys associated with anticlines and synclines, respectively. The summit of the anticlinal ridges may roughly

**Fig. 2.4C** Ridge-like erosional remnants controlled by subvertical dykes and protruding from an extensive sand-covered pediplain in the Arabian Shield, Hail area, Saudi Arabia (Published with permission of © Francisco Gutiérrez 2015. All Rights Reserved)

**Fig. 2.5** Erosional monoclinal scarp on Mesozoic age formations in the margin of the Uncompahgre Uplift, Colorado National Monument, Colorado (Published with permission of © Jon White 2015. All Rights Reserved)

**Fig. 2.6A** Anticlinal ridge (Balut-Boland anticline) in Sarvak Limestone, Izeh Zone, Simply Folded Belt, Zagros Mountains, Iran (Published with permission of © Shahram Sherkati 2015. All Rights Reserved)

coincide with the crest of the structure and the slopes with the fold limbs (Fig. 2.6A). These ridges commonly terminate in periclinal structures at the plunging edge or nose of the anticline. Asymmetric anticlines, usually associated with an underlying blind reverse fault or thrust, tend to produce asymmetric ridges with steeper slopes in the forelimb than in the backlimb. In anticlines with a core of softer sediments, once the resistant rocks are eroded from the crest, differential erosion may result in the development of a valley along the axial zone. These erosional depressions bounded by steep slopes are named combe (French terminology). This is a discordant topography in which the depression coincides with the hinge zone of the anticline (valley-centred anticline) (Fig. 2.6B). Drainage may also breach perpendicularly to an anticlinal ridge through a water gap known as cluse (French terminology) (Fig. 2.6C). These transverse drainages may be related to superimposition and/or antecedence.

**Fig. 2.6B** The Turbón limestone massif (Spanish Pyrenees), an anticlinal structure with an axial valley (combe) excavated into the softer marls and evaporites of its core. Note the periclinal structure on the *left side* of the anticlinal ridge (Image from © Bing Maps)

**Fig. 2.6C** The Millà anticline, Spanish Pyrenees, breached perpendicularly by the Noguera Ribagorzana River, which has been flooded by the Canelles Reservoir. The resulting water gap is called cluse (Image from © Bing Maps)

## 2.7 Perched Syncline

In a concordant structural landscape, the valleys coincide with the synclinal structures. However, erosion in the synclinal zone may be slowed down by the presence of a resistant rock unit removed from the adjacent anticlines, where the correlative strata used to occupy higher positions. Progressive entrenchment under these conditions may lead to the development of a perched syncline (discordant relief). The morphology of the hanging syncline depends largely on the inter-limb angle. Tight synclines tend to produce narrow ridges, whereas perched open synclines are commonly expressed as mesa-like landforms with a concave top. The surface drainage and the groundwater flow tend to converge towards the axis of the syncline and the plunging edge of the relief (Figs. 2.7A and 2.7B).

## 2.8 Conglomerate Pinnacle

These monolith-like structural landforms are conglomeratic pinnacles with vertical cliffs developed by differential weathering and erosion controlled by vertical fractures (Fig. 2.8A). The monoliths may display a wide variety of morphologies (towers, pinnacles, cones, fins) and may reach some hundred metres high (Figs. 2.8B and 2.8C). They occur as isolated residuals or form mazes of monoliths and narrow corridors controlled by the fracture pattern. The formation of conglomerate monoliths requires the concurrence of a number of litho-structural and geomorphic factors, including a thick succession of massive conglomerates; high degree of induration, commonly related to carbonate cementation; vertical fractures with adequate orientation and spacing; and long-term base-level drop typically related to fluvial entrench-

**Fig. 2.7A** Peña Oroel, a perched syncline with tightly folded conglomerates in the upper part of the relief (Published with permission of © Francisco Gutiérrez 2015. All Rights Reserved)