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A mountainous planet. An approximation to the classification of the Earth's mountains

I. INTRODUCTION

The aim of this work is the elaboration of a classification of the Earth mountains. In this taxonomy, it is intended to unify two methods of classification and characterization that integrate both the objective and perceptual elements that are considered as determinants. The taxonomy is constructed using, as an initial criterion, the dimension and volume to specify the concepts of mountain and mountain range. Then, the configuration and distribution of mountains by continents are analyzed. Third, the structural geomorphology works that are key to the generation of a group in which morphology acquires a specific weight and in which lithology is "a basic but not definitive companion" are incorporated. Finally, from biogeography, different "facies" of mountains are extracted, considering latitude and biological and climatic conditions. In this last section, the surface roughness was a fundamental element to represent the mountains of the world (their information is used in cartography as a reference element). To this group of "elementary factors" is added complementary and necessarily synthetic knowledge from the perception of travelers from different eras and with different motivations.

In the working method, the integration of the sources of bibliographic information with the available digital information was considered essential. The bibliography was divided into three well-differentiated thematic sections: geomorphology/geology of a structural nature, works of general biogeography, and studies and stories of travelers and scientists. To this, more specific information on specific areas and documentation provided by travelers, scholars, and scientists since the end of the 19th century was incorporated.

In the second group of sources, a huge amount of digital information was used that was integrated into a Geographic Information System (ArcGIS 10.4) and for its graphic representation, World Geodetic System 1984 was selected. The formats varied depending on the nature of the source: GeoTIFF for raster information and shapefile for different layers of vector information. To achieve better handling and treatment of the data, the global scale for the altitudinal and continental distribution of the mountains and the continental one for the smaller scale representation was chosen as graphic and processing criteria. Digital reference sources included:

- Digital Elevation Model in GeoTIFF format available worldwide and modified from the ASTER GDEM V3 MDE (NASA EARTHDATA, 2018).
- Reference latitudinal grids and Greenwich Meridian in shapefile format (<https://www.naturalearthdata.com/downloads>)
- Oceans, seas , and volcanoes in shapefile format (<http://www.naturalearthdata.com/downloads>, EARTH, 2019).
- Biogeographic realms in shapefile format (<http://www.naturalearthdata.com/downloads>, 2019).
- Delimitation of mountainous areas according to the roughness criteria set by Körner (2011b) and available in shapefile format in Global Mountain Bio-

diversity Assessment (<https://ilias.unibe.ch/goto_ilias3_unibe_file_1047348_download.html>).

A special case was the Antarctic continent:

- Continental boundaries and Weddell and Ross ice shelves in shapefile format (British Antarctic Survey Geodata Portal. Mapping & Geographic Information Center, 2018)
- MDE in ASCII format (<https://www.bas.ac.uk/data/our-data/maps/online-mapping-resources/>)

Finally, the conclusions show as a fundamental contribution cartography in which a taxonomy of the mountains of the world is presented.

II. THE DEFINITION OF THE CONCEPTS OF MOUNTAIN AND MOUNTAIN RANGE

The mountains are undoubtedly one of the most characteristic and representative components of the terrestrial landscape. In addition, they are very common elements because they are present on all continents and in most regions of the globe, covering 24% of the earth's surface. There is, however, a subjective component when defining what a mountain is; what for a Nepalese of the Himalayas is just a hill, for an inhabitant of the European plains or of the British Isles it could be conceptualized as a great mountain. Therefore, an objective definition is needed when specifying what we mean when we refer to the mountain. The task is more complex than it may seem at first glance, because, there is no consensus when proposing a definition applicable on a global scale. A few authors collect numerous works that try to elucidate the best criteria to achieve the definition of mountains, ranging from those that use geomorphological reasons to ecological ones. From all of them, we believe that the following identifying characteristics can be extracted, although not all essential: elevation/altitude; gradients/slope; the domain of rocky terrain; the presence of snow and ice; the succession of bioclimatic floors; high potential energy with sediment movements; evidence in the landscape of quaternary glaciations and finally, tectonic activity and instability. Other authors summarize even more those common denominators until they are left in two: notable elevation and volume.

Regarding the definition of a mountain range, there seems to be more consensus. The degree of continuity is a variable that has been used since ancient times, both for the concept of a mountain range and for its classification. In other cases, has been proposed an arrangement in categories of mountain systems ranging from isolated mountains to large mountain ranges that span continents. Also, the criterion of continuity has been used when defining a mountain range; specifically, it refers to the alignment of rocky volumes, where it even includes volcano clusters.

III. THE PERCEPTIVE TAXONOMIES

A perceptual reference taxonomy can be deduced in which the mountains are divided into three: written, painted, and sonorous. This approach is generated from a perspective with clear evolutionary dyes and a strong traveling, cultural, sports, and scientific feeling. The most impressive perceptual classifications are those that have as reference the volumes of the great Asian mountains, those of the first travelers and explorers who see the Himalayas and the Karakórum. Its great dimensions are appreciated by Andrew Waugh in the Chomolungma and by Henry Haversant Goswin-Austen in the Chogori (renamed later Everest and K2 respectively). This situation was different in the highest and most magnificent European mountains (The Central Alps) which, taxonomically, were the reference until then. The sizing of the European mountain was surpassed that almost fifty years before in Asia the Mont Blanc or *Monte Bianco* had been crowned by Balmat. The European mountain introduced a category that separated its high peaks from the rest in a mixture of the mythical, the reality, the grotesque, and the novel that often intermingled (Tartarín is a good example). The rest of the mountains, unattainable in this article, when not ignored and poorly painted, written or heard, took second place.

Within the perceived mountains, we consider the conquered mountains. Their physical conquest implies, although perhaps not implicitly, a taxonomy in which there are humid, dry, continental mountains or with marine influences; they are all cold, but we can still include another subcategory that includes the Arctic and Antarctic zones. This classification is present from the first moment in which Luis Amadeo de Saboya addresses "his" Abruzzo's ridge in K2, ascends the San Elías in Alaska, trains in Mont Blanc, or directs an expedition to the African Rwenzori. The first expeditions that sought to crown the great peaks of the Earth had a common goal (limited by available techniques) to climb and the higher the better: Lacedelli, Compagnioni, or Bonatti in K2 or Hillary, Norgay and perhaps Mallory in Everest, just to cite some.

From the "difficult" mountain to the repeated mountain, as many Eight-thousanders, as you can (with or without oxygen): Kaltenbrunner or Messner are, among others, an example of this. One more step starts. Conquered the Everest and the K2 the starting shot is given to the specializations depending on the seasonality. In this section, we cannot forget the winter mountain of the efficient Polish (Rutkiewicz, Wielicki, Kukuczka, Kurtyka, among others). To the above are added the extreme and difficult mountains of Patagonia or the Antarctic (the conquest of Paine or Vinson can be good examples). Or the search for extreme difficulty or the "first winter" in European ridges (Bonatti, Rebuffat, Terray to name a few or South Americans (Bonnington in the Paine among others). The extremes are also reached in our mountains, more discreet than the previous examples, but no less important, among others, to point out the conquest of *Urriellu* peak or *Naranjo de Bulnes* by Pidal and Gregorio Pérez "El Cainejo" (1919) or the development in this same mountain of difficulty climbs such as the opening of "Winter Dreams" in 1983 by the Murcian Miguel Angel Díez Vives and Jose Luis García Gallego; no less important is the activity displayed in the Yelmo (opening of the Southeast track) of La Pedriza de Manzanares by the Kindelan or Aguilera or the pioneer ascension of Ramond in 1802 to Monte Perdido. We lack many other mountains and visions, equal to difficult and perhaps less spectacular that, without a doubt, we will be able to include in the following sections.

IV. THE CLASSIFICATION BY CONTINENTS

To explain the location of the main mountain ranges of the Earth, an image that represents a "T" lying to the left can be used, with a latitudinal line of travel in the Western front of America and another transverse, according to the parallels, in mid-latitudes North hemisphere falls. This mountainous alignment would depart from Morocco and the Iberian Peninsula and would reach the coasts of Southeast Asia, crossing even to the main islands of Insulindia, already at considerably lower latitudes, to then enter the Southern hemisphere. This scheme, repeated traditionally, is quite correct since that great "T" lying down encompasses most of the great mountains and mountain ranges, but we must recognize that it is not exhaustive or complete. This image includes only the most recent mountain ranges, linked, as we will see elsewhere in this article, to the latest processes of subduction and collision of plates. However, most of the mountains and mountain ranges of the previous orogeny are excluded, that is, those associated with large tectonic escarpments in sockets and areas of continental Rift as well as the volcanic mountains associated with oceanic hot spots.

V. CLASSIFICATIONS BASED ON BIOLOGICAL AND MORPHOLOGICAL CRITERIA

From the reformulation of Wegener's theory in the 60s of the 20th Century, the morphotectonic bases are established for the understanding of the terrestrial relief and the reflections on the distensive or compressive origin of the great mountain ranges are initiated. With the evolution of natural sciences to the definition of mountains, disciplines such as botany, ecology, or climatology are added. The mountains begin to be interpreted as geo-biosystems with a common past and with bioclimatic particularities directly related to their altitude and geographical location. The sum of the above elements allows two well-differentiated and complementary levels of classification to be obtained: the first one associated with the bioregion, bioclimate, and biotype; the second to a morphostructural domain. It is obvious that in our considerations we do not forget the variety of cases that are logically excluded for reasons of space scale.

1. Bioregions, bioclimas and biotype

Regional and local bioclimatic factors are essential to establish an approach to a mountain taxonomy. In its classification, elements no less important and initially considered are directly involved: the latitude and longitude in which they are located, their elevation and their roughness (in which the slope is introduced as a decisive factor). Some authors consider that precipitation, latitude, orographic shadow, orientation, and geology are factors that determine biodiversity in the high mountains. Most recently approximations zoning is proposed in which the topographic and thermal characteristics are joined and the roughness and slope obtained from digital cartography are included to classify the world in seven climate-defined life zones in mountains facilitate large-scale (global) comparisons. In our work we differentiate up to three types based on these criteria:

Equatorial-tropical mountains: they represent 29% of the total land, 4.0 M km^2 over the total of 13.8 M km^2;

they are exceptionally rich areas in biodiversity. The predominant floor is the frost-free basal with an average temperature of the vegetative period of > 15ºC.

Temperate mountains: 69% of the total areas considered mountainous (9.5 M km^2) are included in this category and occupy a greater extent in the northern hemisphere (7.82 of M km^2) than in the south (1.68 of M km^2). In these mountains, all floors follow each other, depending on the altitude and latitude in which they are located, in a more or less homogeneous way

Polar mountains: they barely mean 2.17% within all mountains (with 0.3 M km^2), not only because of their smaller extent but due to their biotic homogeneity, Körner et al. (2017) do not include Antarctica in their total calculation. The Polar mountains are essentially glaciers, although in many cases they barely exceed 1,000 m. of altitude (Owens and Slaymaker, 2004).

2. Morphostructures and biogeographic and regions

Taxonomies that combine morphogenetic and morphological factors are performed from the large morphostructural sets. The cataloging effort of the large morphostructures makes it possible to relate mountains and large morphostructural sets and, therefore, the mountains are assimilated to a specific genesis, have a characteristic morphological entity, and a dominant lithological composition. We have identified 11 types of mountainous areas related to their tectonic and lithological origin: rift valleys, subduction zones, continental collision, transform plate boundaries, oceanic margins associated with transforming faults, large escarpments, ocean ridges, Cenozoic mountain ranges, partially eroded mountains of the late Mesozoic and late Paleozoic, very eroded mountains of the early Protozerozoic and early Paleozoic and continental shelves. To the morphostructural criteria, it is definitive to add those that the biogeography introduces and, therefore, those that indicate the final character of the mountains. The systematization of these observations is done by classifying the biogeographic realms that divide the globe into seven: Palearctic, Nearctic, Antarctic, Neotropic, Indomalaya, Afrotropic, and Australasia.

Early Protozerozoic and/or Paleozoic Mountains

They are built on Precambrian morphostructures or the oldest Paleozoic lands. They are shields that, due to their antiquity, have undergone intense processes of cratonization, hardening, and deformation and on which large slightly deformed surfaces have been generated. Prolonged erosion processes have acted on these areas that have favored differential erosion and on numerous occasions the presence of characteristic morphological characteristics. At the same time and, favored by their rigidity, they have responded to tectonic efforts by fracturing and generating wide scarps of failure on which massive morphostructures (horst) stand out. They dominate the granitic and gneissic-schistose complexes typical of regional metamorphism and are often intruded by eruptive materials of diverse nature.

Antarctic: mostly within the grounds of the North American and Greenlandic craton

Neotropical: in the Guayano-Brazilian craton

Afrotropical: distributed by the Drakensberg, over the Kalahari craton, the Tsaratanana Massif, the Tanzanian craton, and its prolongation in the Ethiopian massif and the Arabo-Nubian shield.

Indomalaya: in the southwestern end of the Hindustani Peninsula and over the Indian cratón

Paleozoic Mountains

These mountains are located on the so-called ancient massifs and their architecture is built on the materials raised by the Caledonian and Hercynian orogeny and, subsequently, rejuvenated in the Alpine. Their lithologies are similar to the previous type, intermingling intrusive Precambrian and Paleozoic intrusions with peripheral areas dominated by sedimentary materials or a lower degree of metamorphism (quartzites, slates, limestone); the volcanic materials associated with the main faults are frequent. The rejuvenation associated with recent tectonics has generated slightly tilted monoclinal horst and well-differentiated from its sedimentary environment, and relief alignments directed by the main structural lines. The mountains associated with this type have a great heterogeneity in terms of their size and volume and can give rise to mountains of the middle type (central or northern Europe) or, under similar morphostructural patterns, some of the highest, most massive and complex mountains of the earth (Central Asia).

Antarctic: the Appalachians and the Watkins Range of East Greenland stand out.

European Palearctic: in the Iberian Peninsula they are represented by the Central System, Galician-Asturian Cantabrian mountains, and the *Picos de*

Europa and extend throughout the central sector of Europe in the Central Massif and Bohemian massif to extend to the Scottish Highlands.

Eurasian Palearctic: they culminate in the Urals and their insular extension is the mountains of New Zembla.

Asian Palearctic: of great extension they start in the complex physiographic node that supposes the transition between the foothills of the Karakórum and the Pamir and continue towards the northeast on a set of extensive and massive massifs like the Tian Shan and more to the north, that of Altai; this large group of Central Asian mountains continues, heading northeast, towards the Stavonoy, Verkhoyanski, and Cherski mountains.

Australasians: the culmination of the Australian Alps rises at the southeast end of the Australian continent.

Cenozoic Mountains

Mountains of great extension and continuity on rejuvenated or elevated morphostructures in the Alpine orogeny. They constitute a large folded set that emerges, in a dominant way, in the Southern Eurasian margins, and in the American Western margin. These large mountain ranges are associated with the clash of tectonic plates, as in the case of the Alps or the Himalayas, or the existence of subduction areas such as the Andes. They have a great variety of morphologies that correspond to a great lithological diversity; in the same mountain range different carbonated sedimentary facies may appear intermingled with intrusive, metamorphic, and even volcanic elements. Due to their size and complexity, they can be classified into two types. In the first, simple folded structures are included, without excessive complexity and with clearly directed architectures and, in the other, folded structures in which complex morpho-elements intermingle such as riding mantles, failed structures, and simple folds. They are morphological sets that, due to their complexity and extension, are poorly defined on a large and medium scale and clearly defined on a small scale.

European and North African Palearctic: a broad group that begins in the Pyrenean-Cantabrian system and extends through the south of the Iberian Peninsula in the Betic Mountains, North African Rif (Jbel Tidirhine, and Moroccan Atlas; to the east continues in the Alps and the Dinaric Alps and places its appendix in the Carpathians.

Eurasian Palearctic: they constitute transitional sets of marked alpine course between the Alps and the Himalayas.

Indomalaya: the most complex and heterogeneous mountainous knot in the land where the summits of the Nepalese Karakórum and Himalayas stand out.

East Asian Palearctic: mostly located on peninsulas and islands of marked volcanic nature that have their highest elevation in the miocene limestones of the Puncak Jaya or Carstensz Pyramid

Nearctic: fully included in the Rocky Mountains and extend from New Mexico to the Yukon.

Central American Neotropical: transition mountains between the Rockies and the Andes; They are divided into two branches: the Sierra Madre Oriental and the Sierra Madre Occidental.

South American Neotropical: they are located entirely in the Andes and their northern foothills are located in Venezuela and reach the southern tip of the continent in Tierra de Fuego.

Antarctic: located in the Antarctic Peninsula and western Antarctica.

Australasians: their best representation is Mount Cook in New Zealand.

Volcanic Mountains

They are mostly isolated and well-defined morphosculptures on the Earth's surface. These mountains are distributed across all continents and archipelagos. On the continents, they are part of wider mountain ranges, as in the case of North and Central America (Pico de Orizaba, 5,747 m.) And South America (Chimborazo, 6,263 m.) Or as Etna (3,320 m.), within the Mediterranean Alpine domain; nevertheless, there are also examples of marked intracratonic character (Rift Valley). It is the Pacific Island-arch and the central Atlantic back where the largest number of volcanic mountains emerged.

Depending on its origin we can differentiate three major types: those that are located in subductive areas such as the peaceful "Ring of Fire", those associated with intraplate volcanism with "hot spots" such as the Hawaii Islands and those related to accretion areas (Atlantic Islands). Its age is heterogeneous and includes from recent and active volcanism at present, as in the case of the Costa Rican Central Mountain Range, to inactive stratovolcano complexes as in the case of the *Caldera de Taburiente* in the Canary Islands.

Atlantic Insular: located in a group of islands and archipelagos of the North Atlantic, Central or south-central.

Circumpacific insulars: they spread throughout the southern Pacific from the Java Sea in Indonesia to the South China Sea, and reach the Central Pacific; to the north, there are representations in Japan (and, on its Northern margin, in the Kamchatka-Kuriles complex.

Continental: Highlights include the Rift Valley and the Central Mountain Range of Costa Rica (Irazú, 3,432 m.)

VI. CONCLUSIONS

From the previous deliberations, the enormous complexity of the global scale classifications of the Earth's mountains is deduced, since the heterogeneity and variety of their morphologies, lithologies, and biomodels greatly complicate their typification. However, it is possible to approach the mountains in a hierarchical and structured way in layers that allow a progressive and coherent exercise and that also unravels the initial "knot" complex. This exercise is done considering a scalar and thematic hierarchy in three levels. In the first, the mountains are defined on a global scale for which surface models are used in which the relief volume is collected. In our case, the "roughness" criterion based on a digital global elevation model for its calculation has been valid. The second level introduces the morphostructural component into the taxonomy and, in a secondary way and by a necessary simplification, the lithological one. This has allowed us to compare different mountain systems and find similarities that allowed their grouping. Finally, in the third, the biotic component is introduced which, on a scale comparable to the previous one, each mountain belongs to a biogeographic realm with common bioclimatic characteristics. However, the different criteria that outline, in greater detail, the different mountain facies of each set of morphostructures or each biogeographic realm cannot be forgotten.

Also as conclusions, we can consider the repetition of certain architectural patterns of the mountains in distant territories: the Indian Ghates present domestic morphologies similar to those of the South African Drakensberg or those of the Brazilian Serra do Mar: they are, in short, modeling derived from a past common cratonic. In the same way, the complexity of folds, mantles, horseback riding, and faults of the Nepalese Himalayas is reproduced in the Rockies, the Alps, or in the Andes. To this, the deformation associated with Alpine tectonics, the flexibility of the materials, and the action of the glacial and periglacial cold that give them, with different dimensions, a similar aspect are added. The patterns are also repeated when the mountains acquire their final appearance depending on the biogeographic realm in which they are framed; the temperate mountains of central Asia, those of Southern Europe or those of North Africa share a common biogeographic region: the Palearctic. However, they present faciations directly related to their latitude and position on the continent; those of central Asia (Altai, Tien Shan) are much colder and continental than those of the European Palearctic (Alps, Pyrenees) and these, in turn, than those of the North African Palearctic (Atlas). A similar case is that of the polar mountains, the Trans-Antarctic Mountains, or the culminations of Ellesmere, despite belonging to extreme regions of the earth, they are different; the first simplified by the presence of a permanent snow floor and the second with a more complex vertical bioclimatic structure.

The limitations of this classification are evident due to its breadth and complexity and, especially, due to the impossibility of collecting examples in greater detail, in which each set of mountains is considered as something unique and different from the rest. However, we believe that these classification criteria can serve as a reference framework for future larger-scale work.