Journal of Maps

ISSN: 1744-5647 (Online) Journal homepage: www.tandfonline.com/journals/tjom20

Geomorphotectonic approach to geology of the Viñales National Park, Cuba

J.L. Goy, J.L. Corvea, A.M. Martinez-Graña, C. Zazo, C.J. Dabrio, C.E. Nieto & I. De Bustamante

To cite this article: J.L. Goy, J.L. Corvea, A.M. Martinez-Graña, C. Zazo, C.J. Dabrio, C.E. Nieto & I. De Bustamante (2026) Geomorphotectonic approach to geology of the Viñales National Park, Cuba, Journal of Maps, 22:1, 2614771, DOI: 10.1080/17445647.2026.2614771

To link to this article: https://doi.org/10.1080/17445647.2026.2614771

Published online: 03 Feb 2026.

JOURNAL OF MAPS
2026, VOL. 22, NO. 1, 2614771
https://doi.org/10.1080/17445647.2026.2614771

SCIENCE

OPEN ACCESS Check for updates

Geomorphotectonic approach to geology of the Viñales National Park, Cuba

J.L. Goy[a], J.L. Corvea[b], A.M. Martinez-Graña[a], C. Zazo[c], C.J. Dabrio[d], C.E. Nieto[a] and I. De Bustamante[e,f]

[a]Department of Geology, Faculty of Sciences, University of Salamanca, Salamanca, Spain; [b]GAMMA SA, Environmental Consultancy, La Habana, Cuba; [c]Department of Geology, National Museum of Natural Sciences-CSIC, Madrid, Spain; [d]Department of Geodynamics, Stratigraphy and Paleontology. Faculty of Geology, Complutense University, Madrid, Spain; [e]Department of Geology, University of Alcalá, Madrid, Spain; [f]IMDEA Water, Madrid, Spain

ABSTRACT

The geological substratum of Viñales National Park is crossed by fractures and over-thrusts. It includes siliciclastic (Jurassic San Cayetano Formation), carbonate (Late Jurassic to Early Eocene Jagua, Guasasa, Pons and Ancón Formations) and olistostrome (Early-Middle Eocene Manacas Formation) rocks, covered by Quaternary deposits. Cartographic methodology includes Fundamental maps (geologic formations, Quaternary, tectonics and geomorphology) and Auxiliary maps (substratum-structures-drainage, slopes and lithology). Auxiliary maps provide basic information, whereas fundamental maps contribute, by means of superposition and selection, to elaborating the final geomorph-tectonic map as an essential part of the geological map. Results and conclusions are derived from the various cartographies.

ARTICLE HISTORY
Received 9 July 2025
Revised 24 November 2025
Accepted 10 December 2025

KEYWORDS
Geologic formations; quaternary; geomorphology; morph-tectonics Viñales National Park; Cuba

1. Introduction

Viñales National Park (VNP), in the western Guaniguanico Range, consists of Jurassic-Cretaceous carbonated sierras with steep slopes and rounded summits (the so-called mogotes) with Quaternary deposits in the intervening fluvio-karstic valleys, surrounded by siliciclastic schistose shales (San Cayetano Formation) and olistostrome (Manacas Fm) rocks. The sierras form parallel bands oriented NE–SW in the central sector, and NNE–SSW in the southern VNP (Figure 1). The term 'mogote' was coined in Cuba to refer to calcareous relieves with steep sides and rounded tops, very common in Viñales valley (Iturralde-Vinent, 2015; Lehmann, 1960a, 1960b, 1968; Lehmann et al., 1956; Molerio-León, 2006). The only relieves comparable in origin and morphology are found in China, Vietnam and Thailand (Iturralde-Vinent, 2015). VNP is the most emblematic of the protected Cuban natural spaces. It has been rated as a National monument (1979), Cultural Landscape of Mankind (1999), National Park (2001), Cuban Geopark (2021), with pending UNESCO's Global Geopark.

It extends across 9 sheets (Sitio Morales, San Cayetano, Minas de Matahambre, Pan de Azúcar, Viñales, Pons, El Moncada, Sumidero and Cangre) of the E. 1:25,000 Topographic Map of the Cuban Republic (1985).

The relief of low-carbonate and siliciclastic mountains is crossed by structures (Díaz et al., 1989). Carbonates are karstified and eroded, with chains or isolated hills or mogotes (rounded relieves) and residual remains (hums), separated by karstic (poljes, uvalas, dolinas, abras, karstic valleys, etc.) and erosional–structural (fluvio-tectonic valleys, karstic valleys, morph-structural trenches, etc.) depressions.

Mapping was supplemented by previous maps, mainly Lehmann et al., 1956; Lehmann, 1960a, 1960b, 1968, with schemes on air photographs E. 1:40,000, E. 1:50,000 for the central zone (Knipper, 1965 y Knipper & Puig, 1967), eastern zone (Biriukov et al., 1969), NW area of Pinar del Río, sheets 3484-III, 3483-III, 3483-IV (Astajov et al., 1981), western part (Burov et al., 1988), and central part (Martínez et al., 1988). Later on, Vázquez Torres et al. (2000a, 2000b, 2020) published the geological sheets Minas de Matahambre (3483-IV), Constelación del Sur (3483-I) and Cayo Inés de Soto (3484-III); López Rodríguez (2009), Otero-Collazo et al. (2016) and Goy et al. (2014, 2023) published geomorphological maps of the VNP or nearby zones (San Carlos range). Díaz Guanche (2017, PhD monography) and Vázquez Torres et al. (2021) (Geologic Guide of the PNV) published geological maps scaled 1:50,000.

Other consulted maps are the geology of Pinar del Río, E. 100,000 (García et al., 2003, 2005; Martínez, 1994); maps E. 1:250,000 geology (Pszczolkowski et al., 1975, p. 1987), geomorphology (Biosca, 1980;

CONTACT A.M. Martinez-Graña amgranna@usal.es Department of Geology, Faculty of Sciences, University of Salamanca, Square Merced s / n. (37 008), Salamanca 37 008, Spain

Supplemental map for this article can be accessed online at https://doi.org/10.1080/17445647.2026.2614771.

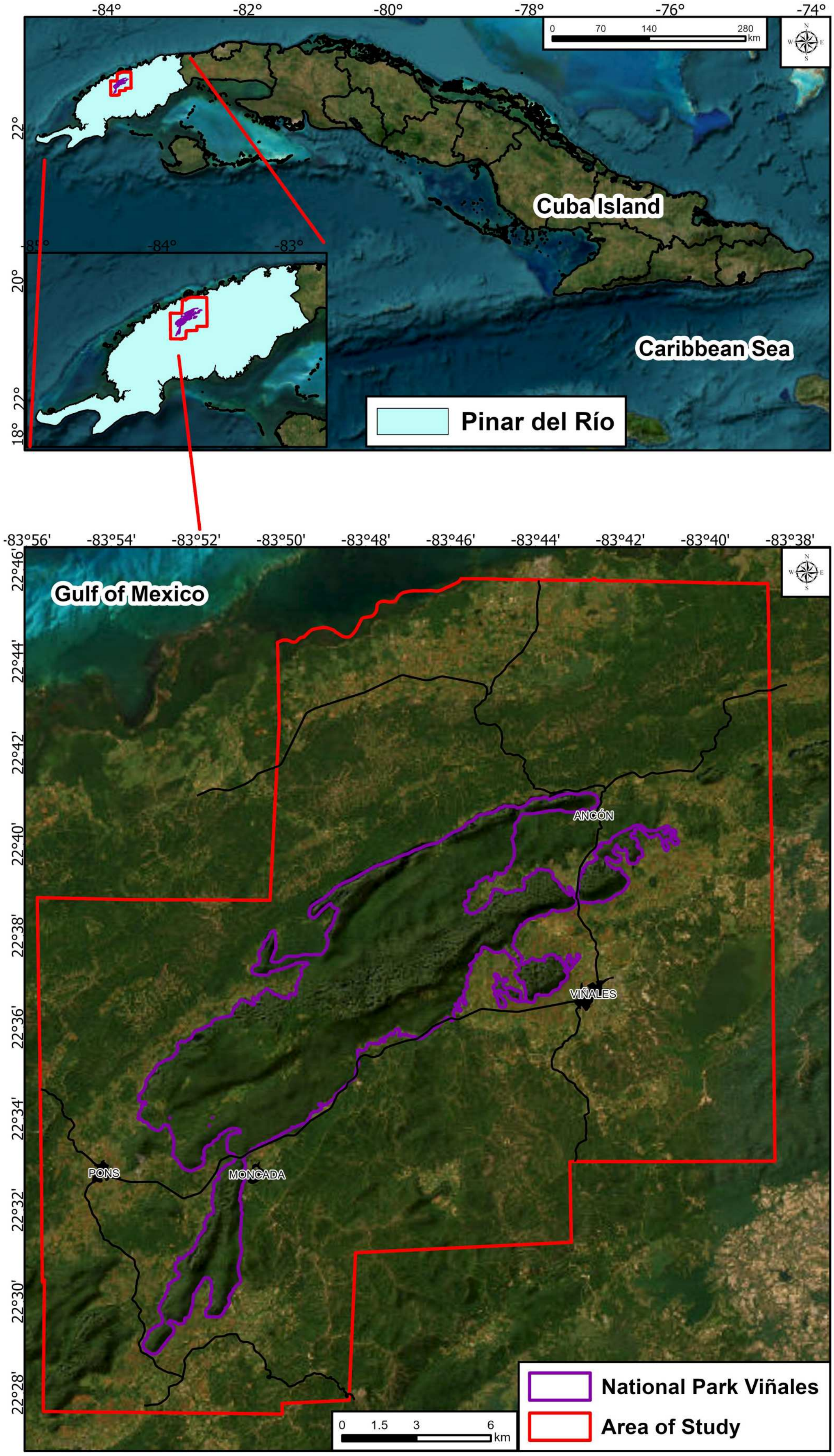

Figure 1. Location of the study área and limits of the VNP.

Biosca et al., 1978), geology of Cuba (Albear et al., 1988; Pushcharovki et al., 1985; Pushcharovski, 1988), Quaternary deposits (Peñalver et al., 2001); maps E. 1:500,000, tectonic map (Pushcharovski et al., 1967, 1996; Shein et al., 1985) and Geological Map of the Republic of Cuba (Linares et al., 1985).

The objective of this work is to improve the geological information of the PNV, in geomorphological, morphostructural and neotectonic aspects, and of the Quaternary deposits, with few references in the maps of this area, and to serve as a basis for the Geomorphotectonic map by facilitating the adjustments of the geological and geomorphological units.

2. Geologic and geomorphologic framework

The basement of the VNP includes folded, slightly metamorphic Early Jurassic to Early-basal Middle Eocene rocks, with three lithologic units: basal terrigenous, intermediate carbonate and upper olistostrome. Some references about the geology of Cuba are: Pszczolkowski et al., 1987/1982; Iturralde-Vinent, 1997, 1998; Cobiella & Cruz, 1999; Iturralde-Vinent et al., 2009; Iturralde-Vinent, 2011.

In ascending order, the lithostratigraphy includes:

1 – Lower to upper Jurassic San Cayetano Fm. Low metamorphic siliciclastics of deltaic origin. 2 – Late Jurassic Jagua Fm. Stratified, fossiliferous marine carbonate and mudstone. 3 – Late Jurassic-Early Cretaceous Guasasa Fm, with four members (Mb): (a) San Vicente Mb: grey, massive limestone with Mogotes morphology. It is informally called Guasasa 1. (b) El Americano Mb: dark, dolomitic limestone. (c) Tumbadero Mb: micritic, chert limestone. (d) Tumbitas Mb: thick-bedded, microgranular limestone. The informal name for the whole is Guasasa 2. 4 – Lower to Upper Cretaceous Pons Fm: Dark, micritic chert limestone with interbedded siliciclastics. 5 – Stratigraphic hiatus of part of the Upper Cretaceous (Coniacian to Maastrichtian). 6 – Unconformable Moncada Fm: 2 m thick, calcareous sandstone with interbedded siliciclastics of K-Pg limit age (Díaz Otero et al., 2001; Iturralde-Vinent et al., 2000; Rojas et al., 2007; Tada et al., 2002). 7 – Concordant limestone, marlstone and calcareous breccia of the Early Palaeocene to basal Early Eocene Ancon Fm. 8 – Early to Middle Eocene Manacas Fm: Olistostrome breccia with sandstone, mudstone, calcarenite, limestone, as well as basalt and serpentinite rooted on the mantle and oceanic crust (Vázquez Torres et al., 2021). This unit acts as a detachment layer for the regional over-thrust nappes. This ensemble is covered with Quaternary deposits including siliciclastics and fluvial, gravitational and marine clays, decalcification clay and semi-endorheic lacustrine deposits.

From a geomorphological point of view, it is possible to distinguish four large ensembles of materials related to the structure. From north to south (Figure 2(A)):

(1) Siliciclastic Esperanza and Santa Teresa Fms sandstones, and San Cayetano Fm shales, and the aligned morphostructural trenches with

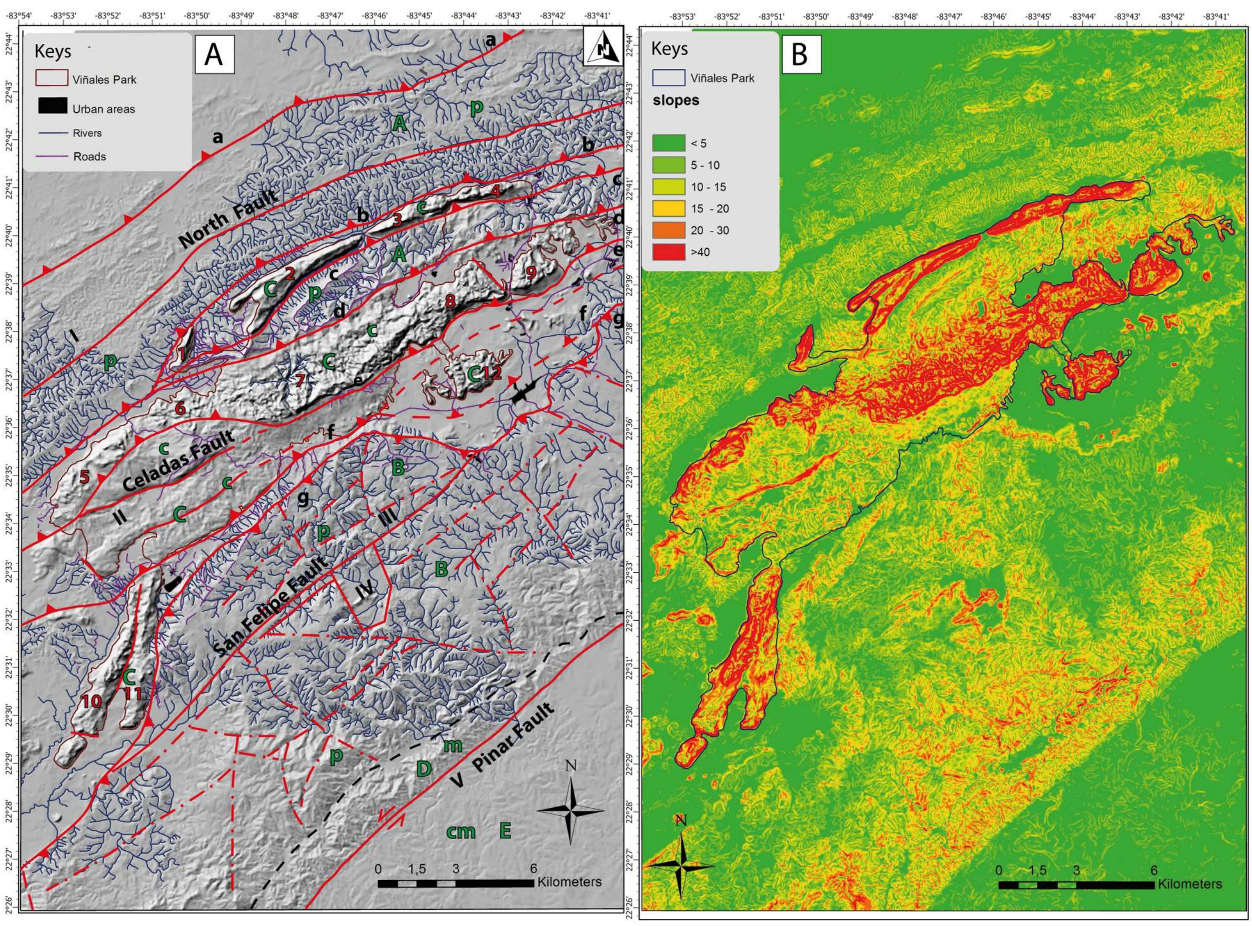

Figure 2. (A) Site names, drainage, substratum, nappes, fractures and lineaments located on the DTM, (B) Slope map.

rocks of the Esperanza, Santa Teresa and Manacas Fms, partly covered by Quaternary deposits, which form a NE–SW elongated convex front.

(2) Siliciclastic–carbonate Elevations of the Northern Shales (ENS), including the carbonated Los Órganos Range, a tectonic window, separated to the north by Manacas Fm, the detachment level of the nappes.

(3) The Core of the Guaniguanico Range (Guasasa, Viñales, Sitio del Infierno, Derrumbada, Chichones, Celadas, Del Medio and Tumbadero ranges), a stacking of over-thrust nappes (Cobiella-Reguera, 2008)

(4) Siliciclastic Elevations of the low metamorphic South Shales (ESS, Cinturón Cangre) (Cruz et al., 2003), separated from the Los Palacios depression by the sinistral /vertical Pinar Fault (Figure 2(A)).

There are just a few specific papers related to Quaternary (e.g.: Cabrera & Peñalver, 2001; Dzulynski et al., 1984; Iturralde-Vinent, 2003; Kartashov et al., 1976, 1981; Peñalver et al., 2022, etc., besides Condis Fernández, 2011 which dated the Late Pleistocene-Holocene mastofauna at Geda cave).

3. Methods

The geomorphologic map of the VNP and surrounding areas was obtained from stereoscopic analysis of air photographs E. 1:62,000 (American flight, 1957) and field campaigns. Some areas with terrain limitations (reduced mobility, dense vegetation, abrupt relief, restricted areas and scarce infrastructures) could not be surveyed, which allows for possible errors. To minimise this factor, the results in these areas were compared with pre-existing maps.

The map was prepared using GIS (ArcGisPro v3.3) with several independent layers: Geologic Formations, Quaternary, Geomorphology, and Tectonics. Digital terrain models (DTM) were used to get topographic information, identify fractures, landforms, drainage patterns and slopes. The 20 and 40 m contours of the digital map were obtained from the DTM with NAD_1927_North_Cuba. Besides the general maps, three auxiliary maps were generated: (1) Place names, drainage, substratum, over-thrust nappes and lineaments; (2) Slopes and (3) Lithology (Figure 2(A, B), Figure 3(A, B)), and two complementary schemes: Viñales-Dos Hermanas polje and Karst types (Figures 6–9).

Chronostratigraphic Map: Geologic formations and Quaternary incorporate age and lithology of Mesozoic and Cainozoic materials, and Quaternary Map, with textures and colours for Pleistocene ages: Lower (purple), Middle (green), Upper (blue) and Holocene (red) (Figure 4(A)).

Superimposing the morphology and lithology layers on this map, the Geomorphologic map is obtained. Superposing Tectonics, Neotectonics and Morphostructure layers, the Morphotectonic map is obtained. Superposition of these two maps generates the Geomorphotectonic mapping (Diagram).

The Lithology Map assigns conventional geologic patterns to the Geologic formations (Figure 3(A y B)). The Geomorphologic Map represents the various

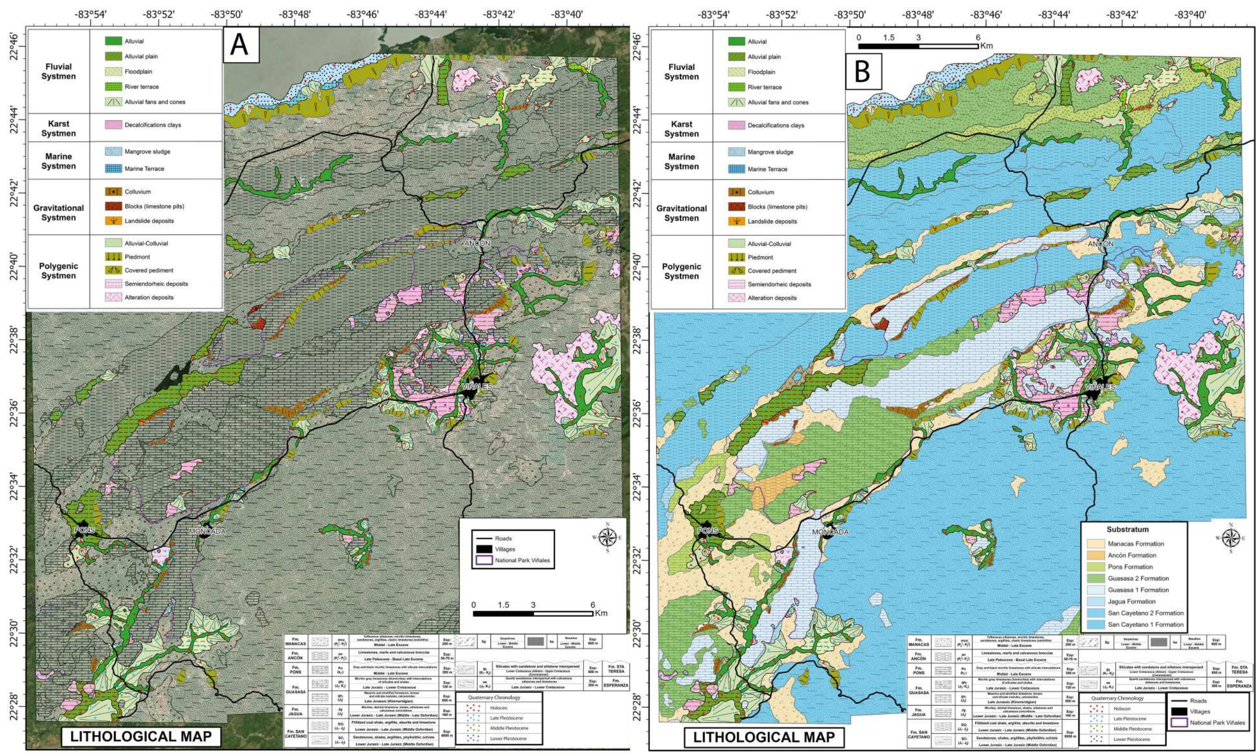

Figure 3. (A) Lithology map (on Google Earth). (B) Lithology map (on Chronostratigraphic).

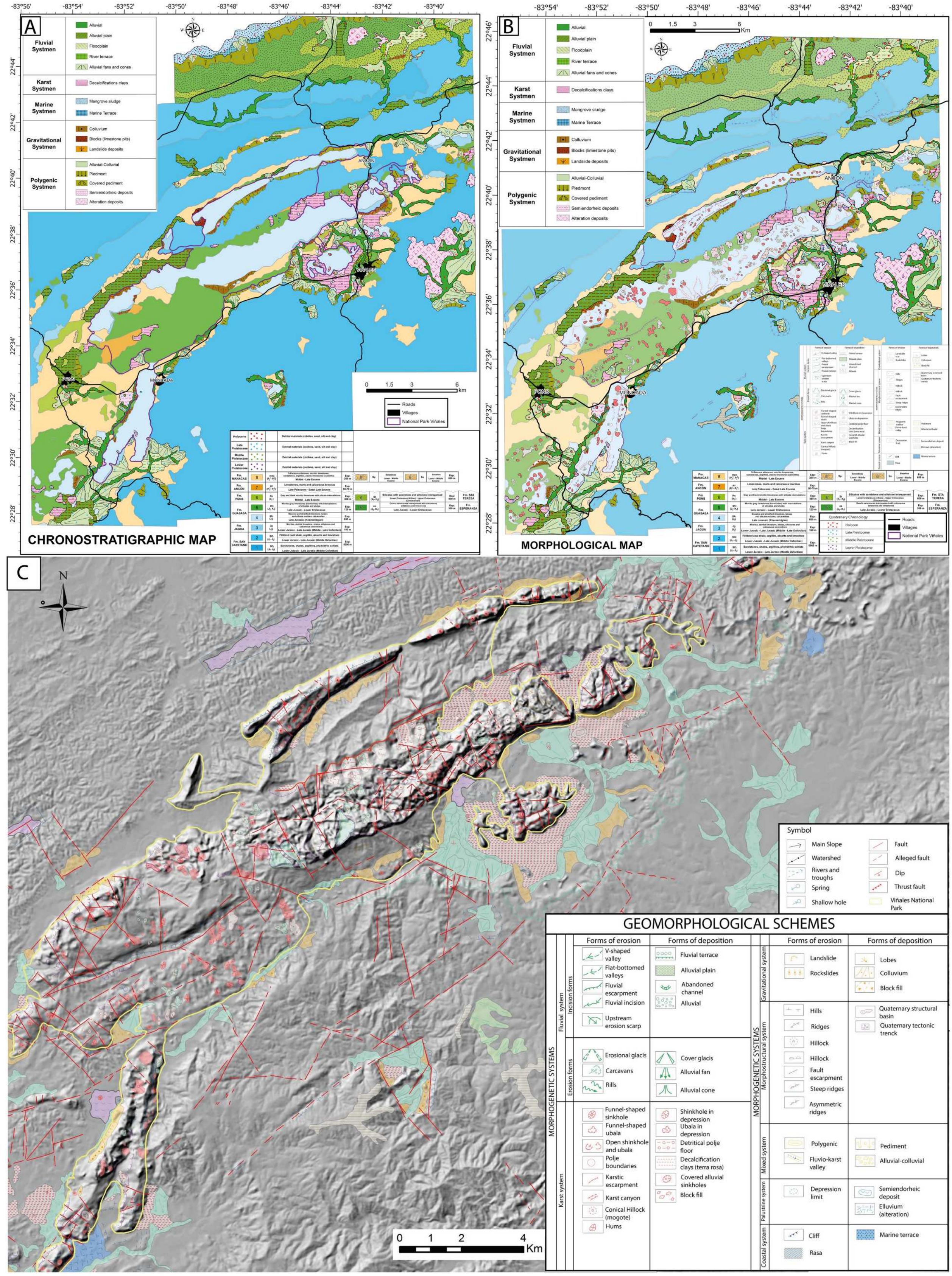

Figure 4. (A) Geologic landforms + Quaternary (Chronostratigraphic). (B) Morphologic Map (on the previous). (C) Morphologic Map on the DTM (Goy et al., 2014).

landforms upon the materials, and allows evaluating the effects of every morphogenetic system over them.

The Morphologic Map represents the morphogenetic systems by means of conventional symbols and colours, separating erosional and depositional forms: fluvial, karstic, gravitational, morph-structural, mixed, lacustrine and littoral. This allows visualising their relative importance, extension and relations (Figure 4(B, C)). Relative ages of deposits and landforms are based upon stratigraphic, geomorphologic and edaphic (paedogenic) correlations.

The geomorphological scheme of Polje de Viñales-Dos Hermanas (Figure 6) allowed us to assign relative ages to Quaternary deposits and poljes according to the relative magnitude of their main scarps, hanging karstic levels (caves), and incision of channels and edaphic evolution of fluvial sediments.

The tectonic map includes dips, folds, fractures, over-thrust nappes and lineaments. The Neotectonic and Morphostructural Mapping uses two red colours to indicate the relative age of faults. Morphostructural morphologies are indicated with purple symbols (Figure 8(A, B)). The Morphotectonic Map distinguishes tectonic, morphostructural and neotectonic features with symbols for observable displacements (horizontal and vertical), changes of dip, over-thrusts and tectonic windows (Figure 8(C)).

A geomorphotectonic mapping was formed superposing the layers geologic formations, quaternary (basic), geomorphologic and morphotectonic (Figure 9). Intermediate morphogeologic and morphogeotectonic maps were also prepared; the last was superposed to the DTM and contour lines to improve relief.

4. Results

Results include auxiliary and basic (main) maps prepared for this report.

4.1. Auxiliary maps

Place names, drainage, materials, over-thrust nappes, fractures and lineaments, which are necessary to understand the study area, including the six aspects of the title.

4.1.1. Place names

Figure 2(A) consigns the main geographic names of relieves, ranges, materials, over-thrusts and faults related to the VNP.

4.1.2. Drainage

Analysis of the drainage pattern of the San Cayetano Fm evidences different responses to fluvial erosion. In highland areas (ENS), there is a dense, incised network. In contrast, in the lowlands (ESS), the pattern is more ample, with angular and rectangular networks owing to structural influence (Figure 2(A)). Vertical incision of creeks indicates uplift (Magaz García, 1984).

4.1.3. Materials (substratum)

When relating morphology, lithology and structure, four elongated N50-70°E, morphotectonic groups, are distinguished (Figure 2(A)). From north to south: (a) rosary-like lineaments NE–SW of siliciclastic materials limited by the Northern Fault; (b) siliciclastic-carbonated materials; (c) the carbonate core of the Guaniguanico range and (d) siliciclastic and metamorphic with small tectonic basins (San Felipe and El Calvario). The curvature of these groups decreases to the north.

4.1.4. Over-thrust nappes, fractures and lineaments.

Movement of nappes towards the NW, with associated ductile and fragile deformation, results from plate compression (Cáceres, 1997, 1998). Siliciclastic sediments overthrust the carbonates and are allochthonous with a detachment surface at the Manacas Fm. The tectonic sequence on top of the Los Órganos range (carbonate sequence) includes San Cayetano shales, surmounted by Rosario range succession, with Esperanza and Santa Teresa Fms (Cobiella-Reguera, 2008). These ranges are a tectonic window, convex to the SW (Cobiella-Reguera, 2008), with internal deformations observable in San Cayetano, Jagua and Guasasa Fms (Figure 2(A)).

Several tectonic scales occur in the Celadas and Medio ranges, and there is a change to SSW-NNE in the direction of the calcareous Quemados range; these are related to faults parallel to the direction of movement (Pérez Gil, 2010).

4.2. Slope map

They help to interpret landscapes (Figure 2B). Contours were selected according to geomorphologic criteria: (a) less than 5° are essentially flat areas with Quaternary deposits (polje surfaces, uvalas a large dolines), not incised fluvial valleys (alluvial fans, flood plains), and structural basins (bottom of tectonic windows, morph-tectonic basins); (b) 5–10°, low slope zones: alluvial cones, piedmonts and colluvium related to karstic depressions and slopes of abrupt relieves; (c) 10–35°, gentle slopes in mogotes hills (rounded) areas, conical, ruinous hills, watersheds in shale outcrops; (d) 35–68°, abrupt slopes, typical in ‘mogotes ranges’, associated to dissolution and fall of blocks and (e) over 65°, scarps and sub-scarps, associated to over-thrust nappe fronts, fault planes and karstic canyons (abras).

4.3. Lithology map

A representation of the geographic location and extent of the materials occurring in the study area by means of conventional patterns. This allows us to investigate the behaviour of lithology faced to fluvial and karstic erosion, and the occurrence of morphologies according to lithology and structure. It helps to understand the distribution of karst types in the zone (Figure

3(A, B)). Lithology is one of the most influential parameters in the incision of relieve which, together with regional and neotectonic uplift, allows to deduce various sectorial and local behaviours.

4.4. General maps

4.4.1. Map of geological formations

According to lithologic variations, two types were distinguished in the San Cayetano Fm. These roughly coincide with the Southern and Northern siliciclastic elevations: the former are mainly coarse siliciclastics, whereas the latter is made mainly finer grained siliciclastic, carbonaceous and carbonate. Two ensembles are also visible in Manacas Fm (see, for instance, Ferrazola-Bermúdez et al., 1964), although they were omitted in this map. Serpentinite and basaltic bodies are tectonic scales coming from the ophiolite belt or the volcanic arcs (Figure 4(A)).

4.4.2. Quaternary map

This is a specific map, essential for understanding the genesis and evolution of karstic, morph-structural and fluvio-tectonic depressions.

They can be grouped into three bands parallel to the over-thrusts (Figure 4(A)). (a) Littoral and pre-littoral Northern Zone with marine (terrasses and mangrove swamp), fluviatile (glacis, alluvial fans, alluvial plains and terrasses) and gravity (associated with Galeras, Ancón and San Vicente ranges) deposits. Benítez Frómeta et al. (2023) report up to 20 m in thickness. (b) Central Zone, including the majority of the main depressions (Pan de Azúcar valley and Poljes of Ancón-Las Casas, San Vicente, Valle del Silencio, La Jutia, Sumidero Zacarias, Valle de Pons, Los Cañadones, Santo Tomás and Viñales-Dos Hermanas), where decalcification clay and fluvial deposits predominate. (Figure 7). (c) Southern Zone. Includes fluvial and tectonic valleys (Cuyaguateje river, Las Tumbas and Isabel María), and the tectonic windows of San Felipe and El Calvario, with fluvial and gravity deposits, over 30–40 m in thickness (Acevedo González, 1971).

The most representative Quaternary deposits with a variety of sediments, morphologies and soils occur at the Viñales-Dos Hermanas and San Vicente poljes (Figure 5), where a relative chronology based upon geomorphology and paedogenic evolution of the decalcification clays was deduced. From south to north, the catena comprises red ferralitic soils, lixiviated red fersialitic soils, and fersialitic leached reddish to yellowish soils (Febles et al., 2016; Jaimez et al., 2006; Ortega & Acevedo, 1987;), which we assigned respectively to Lower, Middle and Upper Pleistocene and Holocene.

Materials around the mogotes in central El Valle and Dos Hermanas poljes are of karstic (decalcification clay), fluvial (terrasses, alluvial plain, channel, alluvial fans and cones), paludal (semi-endorheic in the northern sector, close to the two large Palmerito and Novillo sinkholes) and gravity (colluvium, piedmont and alluvial cones) that form an apron at the base of the main escarpment (Figure 5).

4.4.3. Geomorphologic maps

The carbonate ranges, separated by the detrital deposits of San Cayetano Fm, are most characteristic in the Morphologic and Geomorphologic Maps. Isolated or aligned conical hills (mogotes) with tower, cone and cupule shapes dominate. The carbonated ranges are separated by mostly karstic depressions of various origins.

The main morphogenetic systems are (a) morphostructural, where the main geomorphologic systems control the relief and the landforms that depend on the relations between lithology and structure; (b) karstic, where the materials most prone to karstification are the Guasasa Fm. and San Vicente Mb [Guasasa 1], followed upwards by El Americano, Tumbadero and Tumbitas Mbs. [Guasasa 2], and less Jagua, Pons and Ancón Fms and (c) fluvial, as rivers and creeks, which control several depressions (Viñales-Dos Hermanas, Santo Tomás valley, Pan de Azúcar and Silencio valley) (Figure 6).

The main depressions represented are Viñales-Dos Hermanas, San Vicente, La Jutia-Sumidero Zacarias, Santo Tomás, Ancón-Las Casas, La Cuevita, and Pan de Azúcar poljes, the tectonic El Silencio valley, the North Fault morphostructural trench, the Boquerón del Infierno tectonic front and San Felipe Tectonic Window (Figure 5 and Figure 7). Most of these depressions have been proposed as areas (GIA) or points (GIP) of geologic interest (Corvea et al., 2006, 2014, 2020; Goy et al., 2023; Vázquez Torres, 2017; Vázquez Torres et al., 2019, 2021). Other relevant features are the paleo-surfaces in the south area, and glacis to the north and south (Figure 6)

The relative chronology of poljes is based upon geomorphologic criteria: incision in the erosional morphologies, superimposition and incision into deposits: (a) encasement of the base of depressions with respect to the main escarp, as deepening uses to be caused by dissolution and/or erosion of the bottom; (b) control of caves hanging along the carbonate slopes of the ranges that limit depressions, measured with respect to the bottom and (c) measurement of the incision of creeks in the basin, occurrence of staircase terraces (Viñales polje), and partial elimination of the basin infill.

Analysis of Viñales-Dos Hermanas polje (Figure 5) reveals the encasement of the main escarp (above 150 m in the north sector), the incision of El Tejar and Novillo creeks into the sediments of the basin bottom which formed stair-cased terraces east and west of the basin, the staircase of the bottom sediments

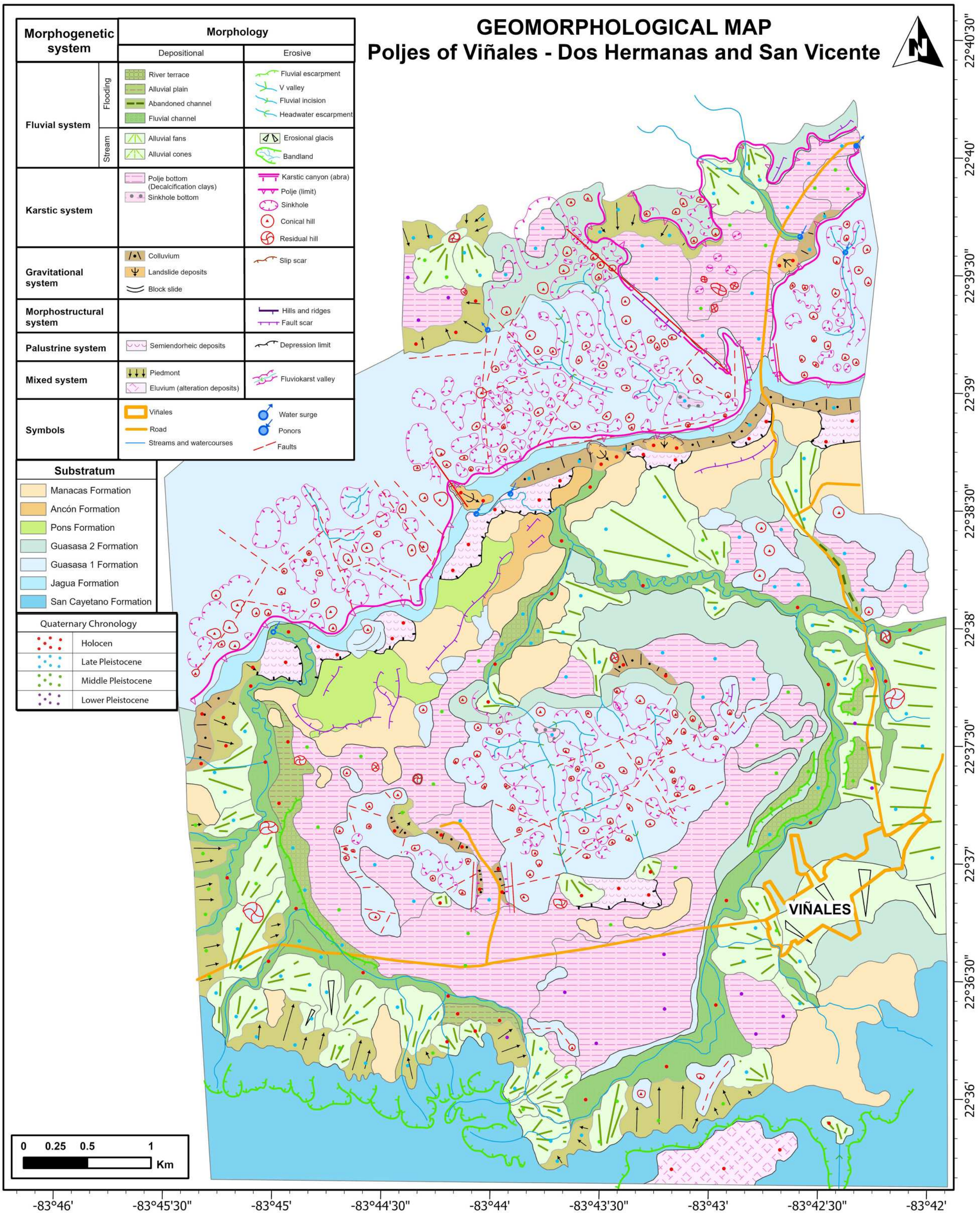

Figure 5. Geomorphologic scheme of Viñales-Dos Hermanas and San Vicente Poljes.

towards the north forming small escarps noticeable both on the field and on the paedogenic evolution. All in all, this suggests a general tilting to the north responsible of the hanging karstic systems between the elevation 235 m and the base level of the polje (Acevedo González, 1971; Díaz Guanche, 2017; Magaz-García, 2021; Molerio-León, 2021; Molerio-León et al., 1999; Molerio-León & Flores, 1997; Novo et al., 2005; Otero-Collazo et al., 2016). This is related to general epeirogeny and neotectonism, proximity to the coastline and successive glacial-eustatic sea level oscillations, which caused changes in the base level of the karstic system. Up to twelve levels of caves have been cited at the Guasasa range (Magaz-García, 2021; Novo et al., 2005) which have been increased in this paper to twenty levels and sub-levels, and correlated to the isotopic curve by Shackleton (1995) and Lisiecki and Raymo (2005).

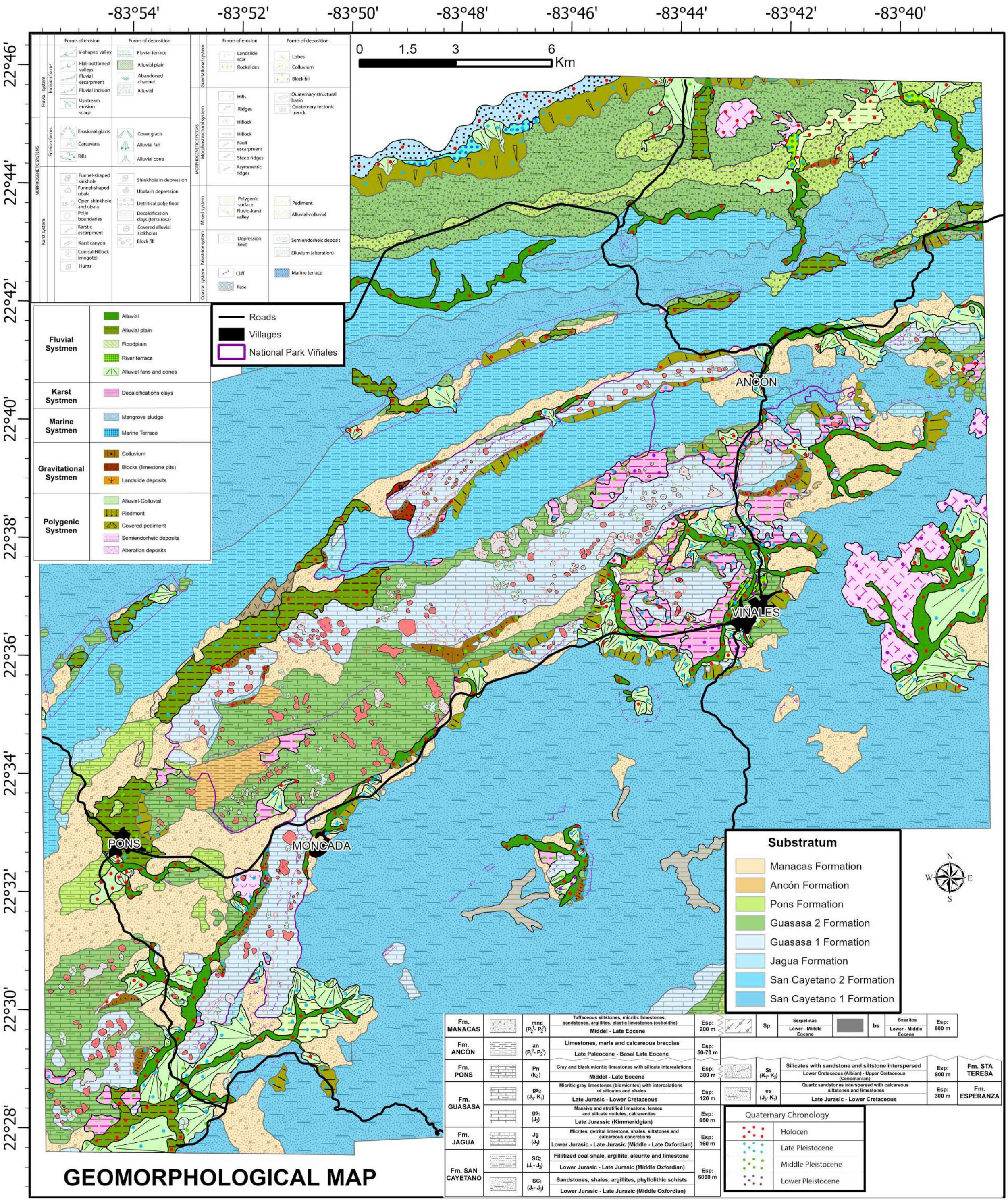

Figure 6. Geomorphologic Map with patterns of lithology.

In general, two types of karst have been distinguished, taking into account lithology and structure: cupula and ruinous (López Rodríguez, 2009). Later, Goy et al. (2014) described several more types (Figure 7): polygonal, conical, fluvio-karstic (in the cupula type), rectangular, tower-like (in the ruinous type), and covered with Quaternary sediments (at the bottom of depressions). The origin of these types is thought to be related to climate, lithology and geological structures, as the region was being uplifted. Recent (Late Pleistocene and Holocene) movements have rejuvenated the drainage pattern and creek incision, as well as generated closed depressions and conical hills. This produced subterranean channel patterns (endokarst) with hanging caves at various elevations owing to oscillations of the local base level and general (sea level) changes.

An additional morphologic feature related to erosion/dissolution processes is the verticality of mogote slopes, as their bases were undercut by lateral erosion

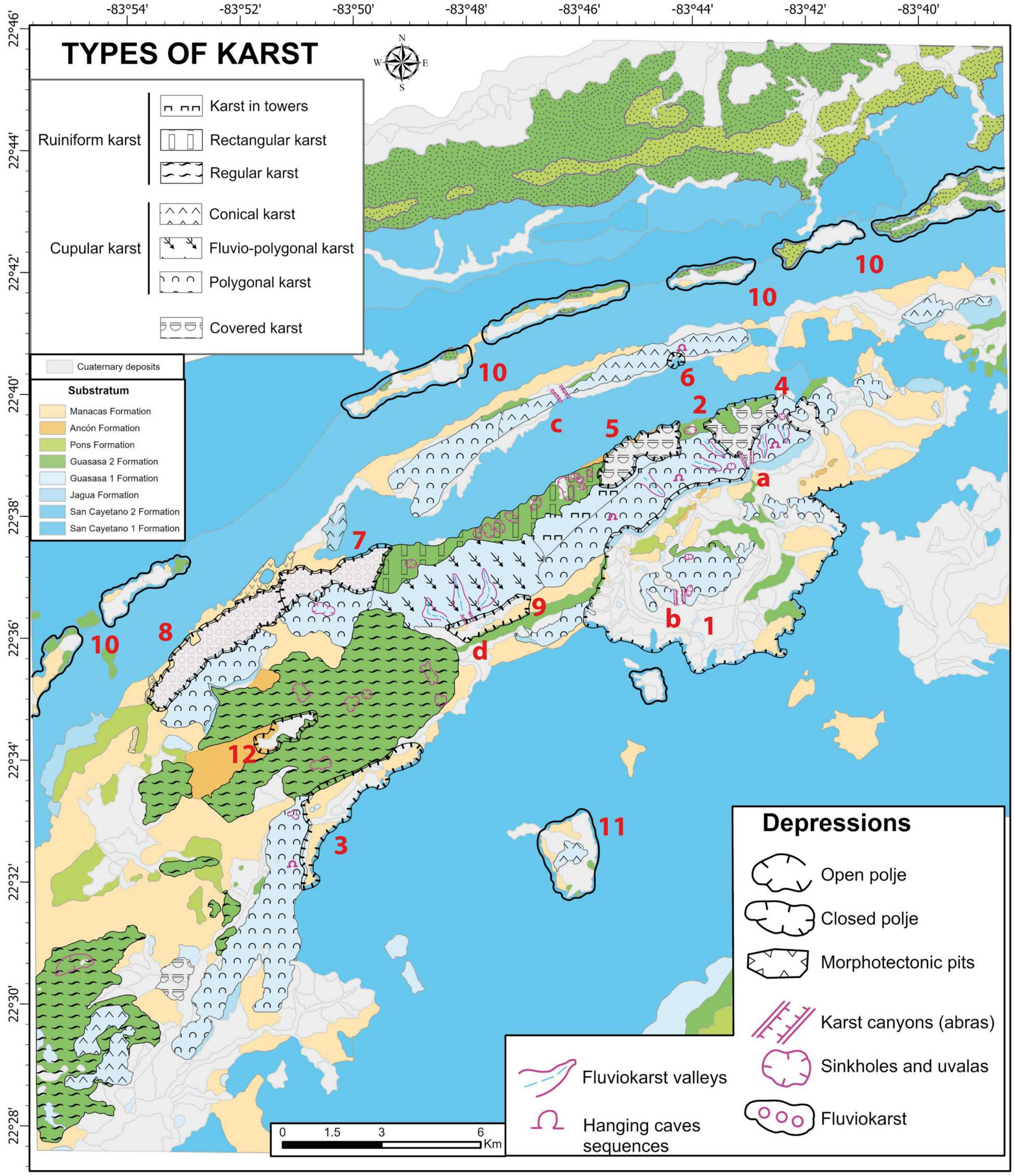

Figure 7. Scheme of the variuos karst types. Legend: Main depressions: 1-Viñales-Dos Hermanas; 2-San Vicente; 3-Santo Tomás; 4-La Jutia-Sumidero Zacarias; 5-Ancón-Las Casas; 6-La Cuevita; 7-Pan de Azúcar; 8-Valle del Silencio; 9-Boqueron del Infierno; 10-Morphotectonic trenches; 11 – San Felipe Trench; 12-Los Cañones. Canyons (Abras): (a) Puerta de Ancón: (b) Dos Hermanas; (c) Abra de Ancón; (d) Cañón Boquerón del Infierno.

of rivers and lakes (Moleiro-León, 2003, 2006), (Figure 2(B)).

4.4.4. Tectonic maps

The tectonic map shows the structures recognised in the VNP: faults, over-thrusts, folds, dips and lineament (Figure 8(A)). The Neotectonic and Morphostructural Map superimposes to the former with a red colour the recent fractures and associated symbols, and other morphostructural symbols (Figure 8(B)), distinguishing: (a) Real, which cause visible horizontal and vertical displacements of materials and landforms, evidenced by changes in dip, morphological steps, mountain fronts with escarps connected to structures, lineament of tectonic trenches along a front, etc. (b) Supposed or deduced, drawn as dashed lines, which are recognised by changes in the drainage pattern (rectification of fluvial courses, creek inflexion following

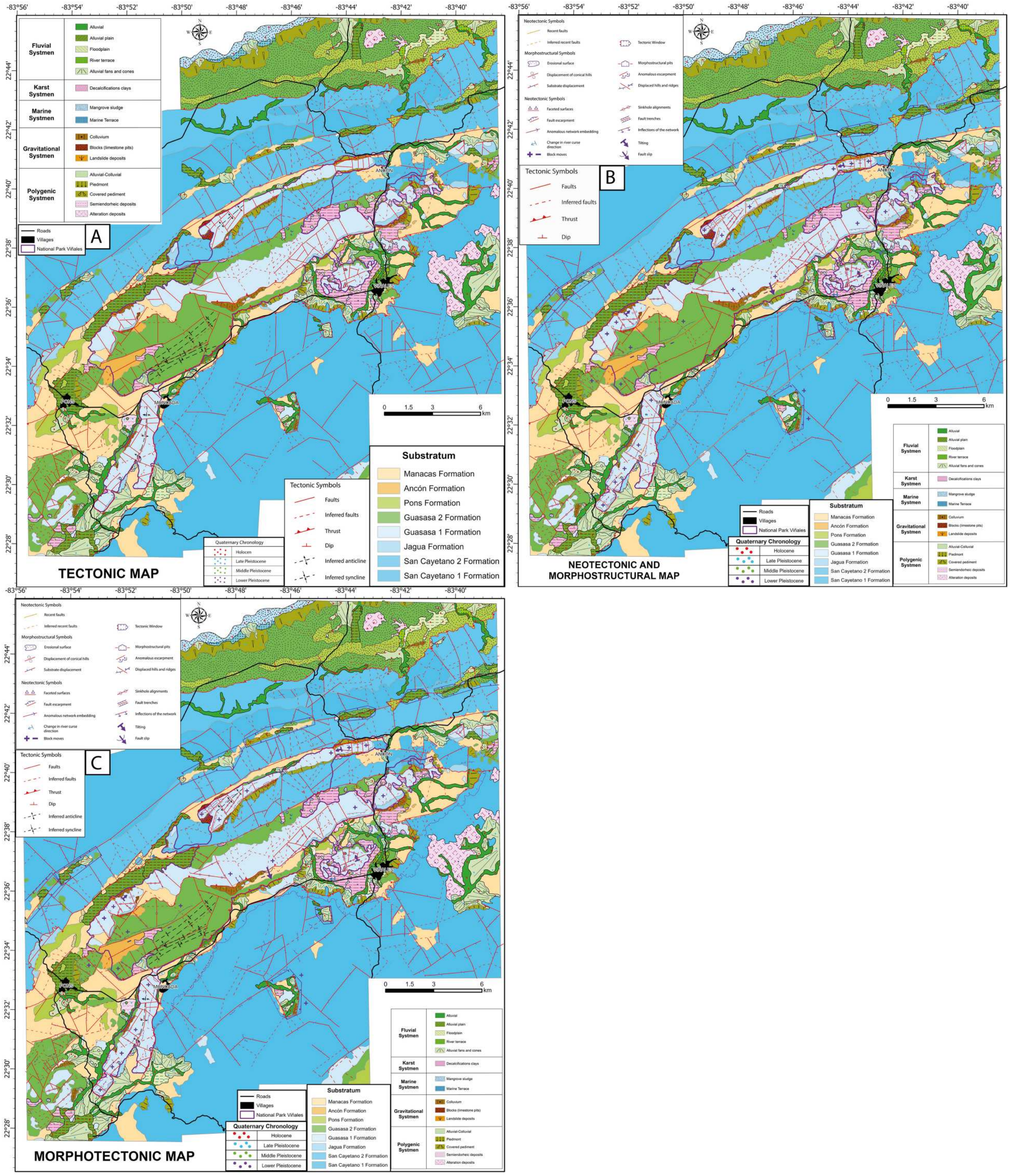

Figure 8. (A) Tectonic Map. (B) Neotectonic and morphostructural Map; (C) Morphotectonic Map.

the structure, and Z morphologies), lineaments of dolines, uvalas and poljes, and rectilinear walls of tectonic trenches. The main tectonic lineaments in this map correspond to large over-thrust nappes and local faults (North, Celadas, San Felipe, and in the southern part, Pinar)

These structures follow the directions of mountain ranges (50–70° N) and must be coeval, or slightly younger, than the nappe emplacement (Late Palaeogene-Early Low Eocene), but they have been reactivated later.

A second group of faults, with directions 150–170° N (normal to the former) are probably connected to differential movements of the nappes during, or immediately after, over-thrusting (a time of maximum compressional stress, Díaz-Guanche, 1999).

A third group of faults, directed 20–30° N, is oblique to the axis of the nappes and is considered posterior, perhaps related to the movement of El Pinar Fault (Díaz Guanche, 2017).

Investigation of the fractures with geomorphologic indicators of recent movements suggests that a

Sheet 1. (1) Nappe front at Guasasa range, with sediments of Manacas Fm in the foreground. (2) A detail of the former. Fault plane with talus deposits, mogotes and underground hanging systems, tilted to the west. (3–4) Viñales range over-thrust nappe front. Isolated mogote (hum) in 3, and talus deposits in 4. (5) Over-thrust front of the western Viñales range, with vertical fracture planes. Also, El Infierno ranges to the far end. (6) A detail of the previous. (7) Fractured western Dos Hermanas mogote and Del Infierno range. (8) A vertical, trapezoidal fault plane in la Costanera (NE Ancón range). (9) Partial view of Ancón and San Vicente ranges with mogotes morphology (seen from the south). (10) Structural La Cuevita Polje between the two ranges of the previous picture. A block tilted to the west reflected in the dip of the mountain tops and the hanging underground systems. (11) Detail of the fault plane in the Ancón range. (12) A faulted mogote (triangular fault plane) with slope deposits, SE San Vicente Polje. (13) Trapezoidal fault plane related to a deep fracture buried under deposits of Viñales valley (SW Mogote del Valle). (14–15) Fractured conical mogotes, Dos Hermanas polje. A displacement of over 30 m is visible in 15.

majority of these are directed 50–70° N. Detail tectonic mapping of the fractures that generate morphologies specific of recent tectonics, together with morphstructure (trenches, uplifted and downthrown blocks, displacement of hills, creeks, etc.) allowed interpreting the dynamics of the various sectors (Figure 8(C)).

4.4.5. Morphotectonic map

This map reveals that the main tectonic structures are related to the large Jurassic (San Cayetano Fm.) and Eocene (Manacas Fm.) nappes (Figure 8). Several aspects of these are shown in Sheet 1 (Photographs 1, 2, 3, 4, 5 & 6). Recent structures experience displacements after this second phase, e.g. North Fault, southern faults of Celadas, del Infierno, Viñales and Guasasa ranges, and San Felipe and Pinar faults, among others (Sheet 1, Photographs 7, 8, 9,11,12, 13, 14 & 15).

These large neotectonic faults and active nappe fronts display geomorphologic indicators of recent movements, such as fault escarps (Lam. 1, Photographs 4, 5 & 6), anomalous escarps, fault trenches, faceted (trapezoidal and triangular) faces (Lam. 1, Photographs 5, 6, 11, 12 & 13), displacement of substratum (Sheet 1, Photographs 7, 14 and 15), displaced hills and crests with associated talus deposits, lineament of geomorphologic elements (dolines, uvalas, thalwegs and trenches), separation of hills (mogotes), inflexions of the drainage pattern, and anomalous incision of riverbeds, and tilting of blocks (Sheet 1, Photographs 2 and 10), among many others.

The alternate bands of carbonate and siliciclastic deposits generate different morphologic features: drainage patterns in siliciclastics are well developed, whereas the ones in carbonates are discontinuous and sub-superficial owing to dissolution processes, with a characteristic karstic modelling (poljes, dolines, caves, underground galleries, karstic defiles …).

Diverse areas of tectonic behaviour are observed in the siliciclastic realms of San Cayetano Fm: recent activity with numerous Quaternary faults at ENS, as compared to the more scarce ones in the ESS. This type of faulting is scarcer in the Manacas Fm.

Vertical movements started in Elocene-Oligocene times (Cabrera et al., 2012; Díaz et al., 1989; Díaz Guanche, 2017; Estévez-Cruz et al., 2021; Iturralde-Vinent, 1998) when the compressional movements ceased, and produced uplifted and downthrown blocks. These movements caused fractures, horsts and grabens during the Pliocene and Quaternary. Neotectonic fractures represented in the map indicate that the main recent movements are associated with the 50–70°N system, as shown by the increased number of fractures in this time. These fractures have influenced the fossil and present karstic systems, coupled with oscillations of local base level and regional uplift. Vertical movements to the west of the El Pinal Fault, detected by geophysical methods, are less than 0.5 mm/y at the Guaniguanico range, with uplift rates of 0.5 mm/yr for the Los Órganos range (Lilienberg, 1984).

4.5. Geomorphotectonic mapping

It is obtained by superimposing Chronostratigraphic, Geomorphologic and Morphotectonic mapping. It represents de geologic materials of the substratum, and superficial formations with chronology and landforms, with special interest in karstic and morphstructural, and main tectonic and neotectonic structures (Figure 9)

This map allows to deduce various types of materials and landforms, their response to erosion, and the processes responsible of changes during their lapse of activity: palaeogeopraphic changes, diverse behaviour of sectors owing to different neotectonic activity such as block tilting (San Vicente, Chichones and Tumbadero ranges), changes in the direction of river courses (El Tejar and El Novillo rivers on Viñales-Dos Hermanas polje, Pan de Azucar river on Silencio valley), anomalous uplifting (del Infierno range, with a hanging karstic canyon, Guasasa range with numerous hanging caves and galleries), abandonment of landforms (fluvial courses, karstic canyons at Puerta de Ancón and the entrance to Dos Hermanas valley), etc.

Another way to obtain a Morph-geologic map is by crossing the Morphologic and Tectonic Maps, with cartographic schemes (dashed lines). A Morphogeotectonic map (similar to the Geomorphotectonic) is obtained by superimposing the Lithology, the Neotectonic and the Morphostructural to the Morphogeologic map. Superimposing the Morphogeotectonic map to the DTM and topography incorporates the relieve (Figure 10).

From the various maps produced, based on photointerpretation and field verifications, we have gained knowledge of a series of geomorphological and neotectonic processes affecting geological materials and Quaternary deposits. This has allowed us to deduce a series of palaeogeographic changes that occurred during this period, based on geomorphological criteria and the associated Quaternary materials and soils. This has enabled us to develop a relative chronology of these changes, the poljes and the materials that fill them.

Although partial maps of the studied area exist, as mentioned in the introduction, they only cover limited sectors of the study area, and most are at small scales (1:100,000 or smaller). Those that exist at the scale used (1:50,000) are either partial or focus almost exclusively on geological formations, with little reference to the Quaternary, geomorphology, and recent tectonics.

5. Discussion

The final map (Geomorphotectonic) integrates, in addition to conventional geological (chronostratigraphic) formations, lithology and structure, other relevant geomorphological aspects of Quaternary deposits and neotectonics, such as (a) Erosion surfaces, mapped around the San Felipe Basin, south of the PNV, which, given their position exclusively on the San Cayetano Formation (Lower to Upper Jurassic), could be attributed a more recent age, and therefore could correspond to the second global scouring surface (given by King) called 'Kretakic or Post-Gondwanan' (Lower to Middle Cretaceous). (b) Morphostructural basins, associated with what we have called the North Fault, whose origin we have attributed to neotectonic effects (decompression) on an older thrust front; Valleys bounded by fractures, such as the Valle del Silencio (Valley of Silence), whose river course is currently irrelevant due to its fossil nature, are also included. This is because the valley was captured by rivers during the Middle or Late Quaternary as a result

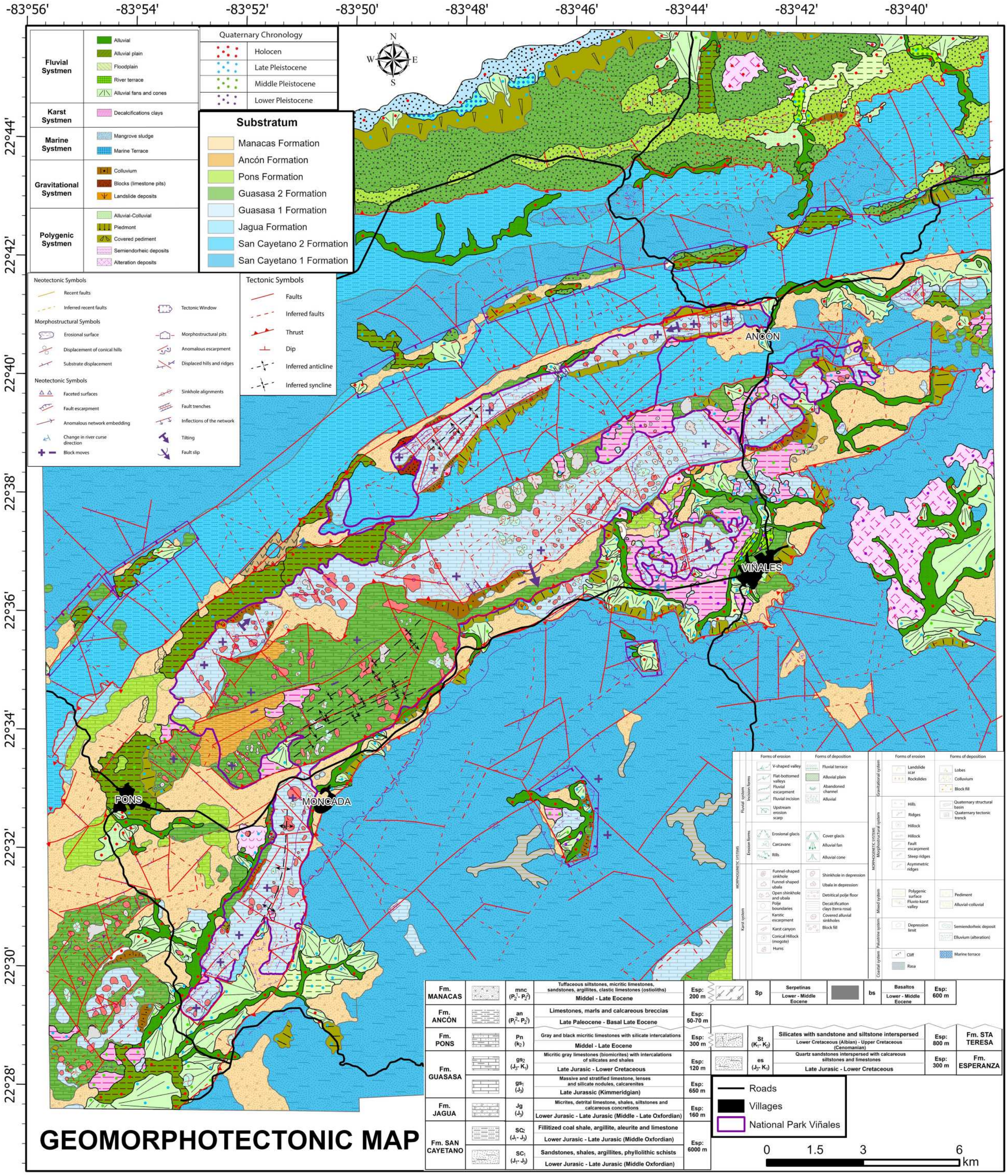

Figure 9. Geomorphotectonic Map.

of neotectonic readjustments (tilting of the Sierra de Chichones). The San Felipe tectonic window (San Felipe Trench) is also shown, bounded by active faults deduced from associated landforms indicative of recent tectonic activity. Recent faults, highlighted in orange, are also noted, allowing us to identify the most active areas. One example is the Celadas Fault, which has given rise not only to the uplift of the Boquerón del Infierno karst canyon but also to a large landslide of the Guasasa Formation limestones in the Sierra Sitio del Infierno towards the depressed area known as Sitio del Infierno, almost 400 metres lower. (c) Important reference to Quaternary deposits, with an indication of their textural and edaphic characteristics (catena), has allowed us to develop, along with a series of geomorphological processes, a relative chronology of these deposits and the depressions in the studied area. (d) This cartography helps us to visualise, through the symbology used, the different uplifted, subsided and tilted zones,

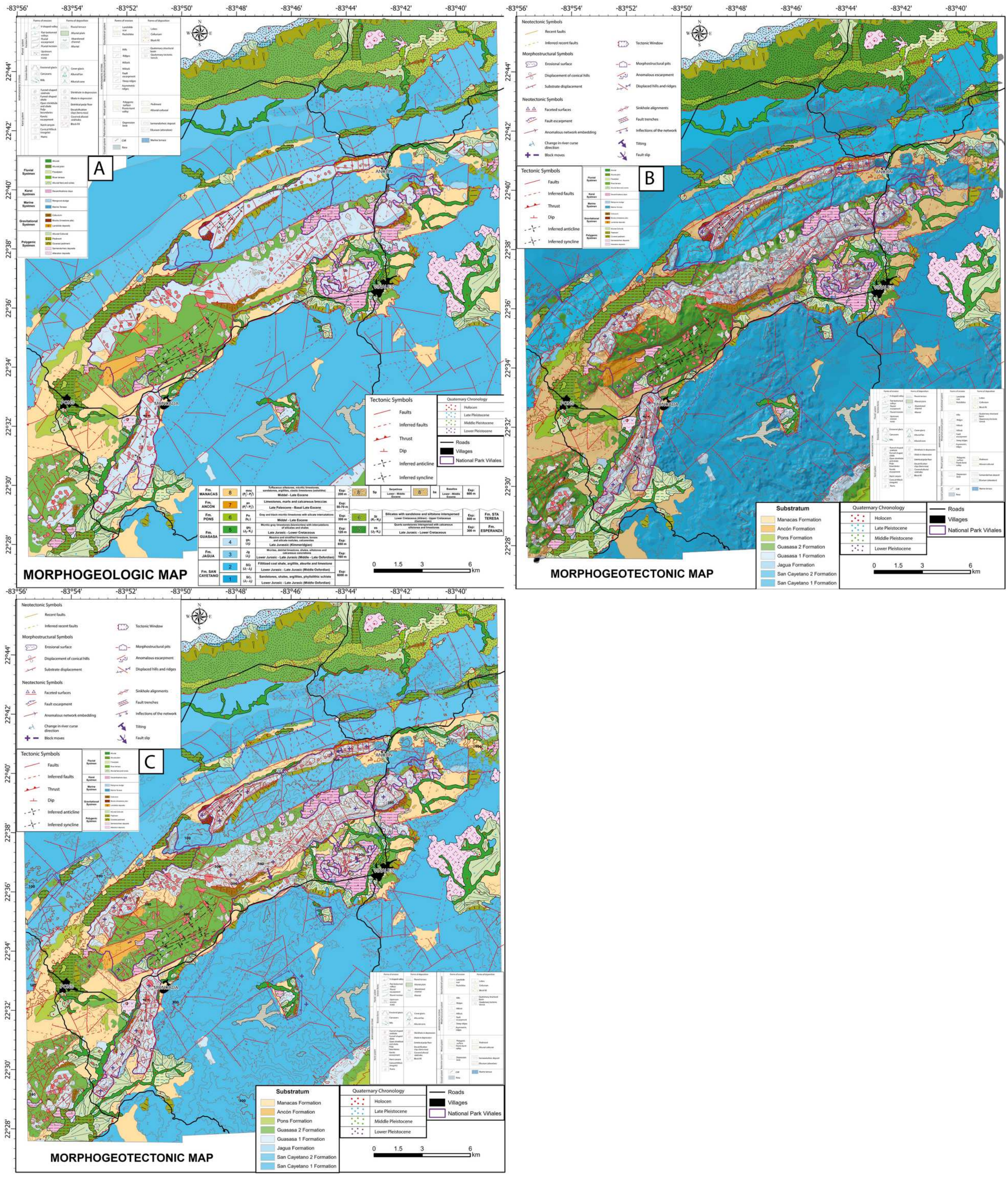

Figure 10. (A) Morphogeologic (morphologic + Tectonic) Map; Morphogeotectonic Map; (B1) On DTM, (B2) with contour lines.

allowing us to evaluate block movements, which in many cases are responsible for palaeogeographic changes and the characteristics of the current relief.

6. Conclusions

– A specific mapping methodology was used to construct a Geomorph-tectonic Map crossing Geomorphologic and Morph-tectonic maps, by the crossing of ten GIS layers.

– This map has been considered the cartographic conclusion, as it supplies abundant data:

(a) Information about uplifted and downthrown areas (ranges and trenches) helps to understand their neotectonic behaviour. They allow us to know their genesis, evolution and chronology in depressions, according to their morphology and Quaternary deposits.

(b) Changes in the drainage network are observed in this map. In the Viñales-Dos Hermanas polje, an abandoned riverbed (old El Tejar creek) from south to north could have generated the Puerta de Ancón canyon (abra), presently without any active watercourse, and Dos Hermanas canyon, probably abandoned by Novillo creek, when they changed directions from S-N to SE-NW after neotectonic movements, probably during the Middle Pleistocene. An additional example is the fossil fluvial canyon Boquerón del Infierno, with an elevation of 150 m, which occurs hanging 250 m above the present valley, and a direction to the SE when the present drainage flows towards the NE. The change probably happened at the beginning of the Quaternary.

(c) Detailed mapping of Viñales-Dos Hermanas and San Vicente poljes allowed to obtain a relative chronology of the depressions based upon morphologies (magnitude of the main escarpment, occurrence of hanging caves and galleries in Viñales and Guasasa ranges), spatial arrangement of Quaternary deposits (incision, offlap, superposition), magnitude of incision in these deposits, paedogenic evolution (increasing development from ferralitic, older, to ferruginous, younger, soils), and neotectonic movements.

(d) Karst type mapping helps to visualise the lateral distribution of karst, and the location of the large depressions :uvalas, dolines, fluviokarstic valleys, canyons (abras) and sequences of hanging underground systems (caves).

Software

ArcGisPro v3.3 was used, with vectorial (dots, lines and polygons) and raster (ortophotos) formats. Working scale was 1:25,000 with Universal Transverse Mercator UTM-Datum-ETRS 89 in spindle 30 as coordinates system.

Open Scholarship

This article has earned the Center for Open Science badge for Open Data. The data are openly accessible at https://gredos.usal.es/ .

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This research was supported by the Spanish Giner de los Ríos Program UAH, 131874B-I00 funded by MCIN/AEI/10.13039/501100011033, and the GEAPAGE research group (Environmental Geomorphology and Geological Heritage) and CEADIR of the University of Salamanca.

Data availability statement

The scientific data obtained in this work are published in the text of the article. However, any extension or detail can be requested from the corresponding author.

References

Acevedo González, M. (1971). Geomorfología de Sumidero y sus inmediaciones, Sierra de los Órganos, Pinar del Río, Cuba. *Revista Tecnológica*, *9*(3/4), 33–54.

Albear, J. F., Boyanov, I., Brezsnyaszky, Y., Cabrera, R., Chejovich, V., Echevarría, B., Flores, R., Formell, F., Franco, G., Haydutov, I., Iturralde, M., Kantchev, I., Ikartashov, I., Kostadinov, V., Millan, G., Mycyzynski, R., Nagy, E., Oro, J., Peñalver, L. L., … Somin, M. L. (1988). Mapa Geológico de Cuba. escala, 1:250,000. Edit. AC. URSS, ACC, IGP.

Astajov, K., Solianik, V., Sesiliev, V., Martínez, D., Fernández, R., Cubiña, J., Dimidov, S., & Santa María, Z. (1981). Trabajos de Levantamiento Geológico a escala 1:50,000 en la parte NW de la provincia de Pinar del Río (Hojas 3484 III, 3483 IV y 3483 III-A).

Benítez Frómeta, P. E., Cruz, E., & Peñalver, L. (2023). Cartografía de los depósitos cuaternarios a partir de datos de pozos en el NNW de la Cordillera de Guaniguanico. *Cuba Cuaternario y Geomorfología*, *37*(1–2), 57–76.

Biosca, L. (Ed.). (1980). *Mapa geomorfológico de la Provincia de Pinar del Río (E. 1/250000)*. Instituto de Geografía. Academia de Ciencias de Cuba.

Biosca, L., de la Cruz, R., Cañas Abril, P., & Isalgué, S. (1978). Geomorfología, mapas 30–31. En: *Atlas de Cuba* (p. 641), Instituto Cubano de Geodesia y Cartografía.

Biriukov, B., Messina, V., Ponce, N., & Navarro, N. (1969). *Sobre los trabajos de búsqueda y levantamiento a escala 1:50,000 realizados en los años 1967–1968 en la parte Oriental de la provincia de Pinar del Río*. ONRM.

Burov, V., Martínez, D., Jusainov, Y., Fernández, R., Dervenev, V., & Uspensky, A. (1988). *Informe sobre los trabajos de Levantamiento Geológico a escala 1: 50 000 realizados en la parte occidental de la provincia de Pinar del Río. (hojas 3382-I, IV; 3383-I, II, III; 3482IV a, c; 3483-III c) en 1981–1985*. Empresa Geominera de Pinar del Río.

Cabrera, M., Orbera, L., Hernández, Núñez, A., Pantaleón, G., Triff, J., & Pérez, C. M. (2012). *Neotectónica y ascenso del nivel medio del mar en Cuba*. Instituto de Geología y Paleontología. Centro Nacional de Información Geológica. Editor: PubliSime. La Habana. Cuba. ISBN 978-959-7117-32-2.

Cabrera, M., & Peñalver, L. L. (2001). Contribución a la estratigrafía de los depósitos cuaternarios de Cuba. *Rev. Cuaternario y Geomorfología*, *15*(3–4), 37–49.

Cáceres, D. (1997). *Estructura Geológica y Pronóstico Preliminar para metales básicos más Barita en la parte central de las Alturas Pizarrosas del Sur* [Tesis doctoral]. Universidad de Pinar del Río, Pinar del Río.

Cáceres, D. (1998). Diferentes fases deformacionales en la porción más meridional de la Sierra de los Órganos. In *Memorias III Congreso de Geología y Minería, TomoI* (pp. 89–92). Editorial C.N.D.I.G.

Carta topográfica de la República de Cuba a escala 1: 25000. (1985). Instituto cubano de geodesia y Cartografía (ICGC).

Cobiella, J. L., & Cruz, E. M. (1999). GeoCuba. Espacios Naturales y Geología Cubana. Libro Guía de la Excursión. Monografías de Enseñanza de las Ciencias de la Tierra. *Serie de itinerarios*, *1*, 79.

Cobiella-Reguera, J. L. (2008). Reconstrucción palinspástica del paleomargen mesozoico de América del Norte en Cuba occidental y el sudeste del Golfo de México. *Implicaciones para la evolución del SE del golfo de México*, *25*(3), 382–401.

Condis Fernández, M.M. (2011). *Interferencias paleoecológicas sobre especies de la mastofauna cuaternaria cubana, conservadas en el depósito superficial de la Caverna Geda, Pinar del Río, Cuba* [Tesis Doctoral, 198p, unpublished]. University of Alicante, Spain.

Corvea, J. L., Blanco, A., Bustamante, I., Farfán, H., Martínez, Y., Novo, R., Díaz, C., & López, N. (2014). Advances in geoconservation in Cuba: Assessment of the guaniguanico range and guanahacabibes plain (Pinar del Río). *Geoheritage*, *6*(1), 1–16. https://doi.org/10.1007/s12371-013-0086-4

Corvea, J. L., Gutiérrez, R., Pascual-Aguilar, A., De Bustamante, I., & Blanco, A. (2020). Integration in the management of the Cuban Protected Areas. *Geoheritage*, *12*:67, 1–16. https://doi.org/10.1007/s12371-020-00491-2

Corvea, J. L., Novo, R., Martínez, Y., De Bustamante, I., & Sanz, J. M. (2006). El Parque Nacional Viñales: un escenario de interés geológico, paleontológico y biológico en el occidente de Cuba. *Trabajos de Geología*, *26*, 121–129.

Cruz, E. M., Maresch, W., Cáceres, D., & Balcázar, N. (2003). La Faja Cangre y sus rasgos metamórficos. Pinar del Río. Cuba. Memorias Geomin. V Congreso de Geología y Minería. *Geología Regional. GREG*, *18*, 125–129.

Díaz Guanche, C. (2017). *El desarrollo del Carso epigenético en el modelo evolutivo de la región central de la Sierra de los Órganos* [Tesis presentada en opción al grado científico de Doctor en Ciencias Geológicas]. UPR Hermanos Saíz, 174p.

Díaz, J. L., Magaz, A. R., Portela, A., Bouza, O., & Hernández, J. R. (1989). El Relieve de Cuba. *Ciencias de la Tierra y el Espacio*, *18*, 33–44.

Díaz Otero, C., Iturralde-Vinent, M., & García Delgado, D. (2001). Evidencias del "coctel" paleontológico del límite Cretácico-Terciario en Cuba occidental. In Inst. Geominero TKT.24-TKT30 *Taller internacional sobre eventos en el límite K/T*. (pp. 1–115).

Díaz-Guanche, C. (1999). *Geología y Geomorfología del Karst en la Sierra de San Vicente. Mención Geología Regional*. Facultad de Ciencias, Universidad de Pinar del Río. 46pp + Anexos.

Dzulynski, S., Pszczolkowski, A., & Rudnicki, J. (1984). Observaciones sobre la génesis de algunos sedimentos terrígenos cuaternarios del occidente de Cuba. *Ciencias de la Tierra y del Espacio*, *9*, 75–89.

Estévez-Cruz, E., Cueto-Gil, C. J., Diaz-Guanche, C., Ramírez-Hernández, R., & Ordad-Hernández, A. (2021). Estudio del Frente montañoso de la zona de Falla Pinar, Cuba occidental, y su relación con la tectónica reciente. *Cuaternario y Geomorfología*, *35*(3-4), 29–53. https://doi.org/10.17735/cyg.v35i3-4.84170

Febles, J. M., Vega, c. M., Tolón, A., Moura, N., Somoza, J., & Díaz, J. R. (2016). Buenos suelos en extinción: la degradación de los suelos ferralíticos rojos en el occidente de Cuba. *Anales de la Academia de Ciencias de Cuba*, *5*(3), 1–2.

Ferrazola-Bermúdez, G., Judoley, C. M., Mijailovskaya, M. S., Miroliúbov, Y. S., Novojatsky, I. P., Nuñez Jiménez, A., & Solsona, J. B. (1964). *Geología de Cuba Editorial Nacional de Cuba* (225p). Editora del Consejo Nacional de Universidades.

García, D. E., Gil, S., Delgado, R. D., Millán, G., Peñalver, L. L., Cabrera, M. C., Denis, R., Chang, J. L., Fuentes, M., Díaz, C. O., Suárez, V., Llanes, A. I., Pérez, R. A., Torres, M., Pérez, C. P., & Díaz de Villalvilla, L. C. (2005). Mapa geológico de la provincia de Pinar del Río a escala 1:100 000 en base digital. *Geociencias*, *1*, 25–35.

García, D. E., Gil, S., Delgado, R., Millán, G., Peñalver, L., Cabrera, M., Denis, R., Chang, J. L., Fuentes, M., Diaz, C., Suarez, V., Llanes, I., Pérez, A., Torres, M., Pérez, P., & Díaz de Villalvilla, L. (2003). *Generalización y actualización geológica de la provincia de Pinar del Río, escala 1:100 000*. Instituto de Geología y Paleontología.

Goy, J. L., Corvea, J. l., De Bustamante, I., Martínez-Graña, A. M., Díaz-Guanche, C., Zazo, C., Dabrio, C. J., González-Delgado, J. A., Blanco, A., & Nieto, E. (2023). Geomorphological Heritage in Viñales National Park (aspiring UNESCO Geopark): Geomatic tools applied to Geotourism. Pinar del Río, Cuba. *Sustainability*, *15*(7), 5704. https://doi.org/10.3390/su15075704

Goy, J.L., Corvea, J.L., Díaz-Guanche, C., Bustamante, I., Martínez-Graña, A.M., Zazo, C., Cruz, R. (2014). Cartografía Geomorfológica del Parque Nacional Viñales (Pinar del Río, Cuba) II Simposio sobre gestión del agua en espacios protegidos. Resúmenes – CD (p. 36), Baracoa, Cuba.

Iturralde-Vinent, M. A. (1997). Introducción a la geología de Cuba. In G. Furrazola Bermúdez, & K. Núñez Cambra (Eds.), *Estudios sobre geología de Cuba* (pp. 35–68). Instituto de Geología y Paleontología. http://www.monografias.com/trabajos39/evolucion-tectonicacuba/evolucion-tectonica-cuba4.shtml#ixzz3eqmsEEJX

Iturralde-Vinent, M. A. (1998). Sinopsis de la Constitución Geológica de Cuba. *Acta Geológica Hispánica*, *33*(1–4), 9–56.

Iturralde-Vinent, M.A., (2003). *Ensayo sobre la Paleogeografía del cuaternario de Cuba*. Memorias Geomineras GQGC, 54–74. V Congreso de Geología y Minería. Geología del Cuaternario, Geomorfología y Carso. La Habana.

Iturralde-Vinent, M. A. (2011). *Ensayo sobre la Paleogeografía del Cuaternario de Cuba* (p. 28). Memorias Geominero.

Iturralde-Vinent, M.A. (2015). Los Mogotes de la Sierra de los Órganos, Pinar del Río: Su origen, desarrollo y desaparición. http://www.redciencia.cu/cdorigen/arca/paper/mogotes.pdf

Iturralde-Vinent, M. A., Batista, R., Casañas, X., Chuy, T., & Díaz, J. A. (2009). *Geología de Cuba para Todos* (148p). Editorial Científico Técnica.

Iturralde-Vinent, M. A., García Delgado, C., Díaz Otero, R., Rojas Consuegra, R., Tada, R., Takayama, R., & Kiyokawa, S. (2000). The K/T boundary impact layer in lithostratigraphy, facies development and paleogeography. *Acta Geologica Polonica*, *28*(1), 1–96.

Jaimez, E., Luis, M. H., & Olivera, J. (2006). Los suelos del Parque Nacional Viñales, Pinar del Río, Cuba. Condiciones genéticas y Ambientales. *Cuadernos Geográficos*, *28*, 195–205.

Kartashov, I. P., Cherniajovski, A., Peñalver, L. (1981). *El Cuaternario de Cuba* (Vol. 356, 145p). Nauka.

Kartashov, I. P., Mayo, N. A., Cherniajovski, A., & Peñalver, L. (1976). Descripción de algunas formaciones geológicas del sistema cuaternario de Cuba, reconocidas recientemente. *Serie Geologica*, *26*, 1–12.

Knipper, A. L. (1965). *Mapa Geológico del área de Viñales. En: Geología de Cuba*. Editorial Nacional de Cuba. Ministerio de Industria. La Habana.

Knipper, A. L., & Puig, M. (1967). Mapa geológico del área de Viñales, escala 1:50.000. In *Geologia i Poleznye iskopaemye Kuby* (Vol. 5, pp. 32–42). Moskva.

Lehmann, H. (1960a). Las áreas casticas del Caribe. *Revista Sociedad Geográfica de Cuba*, *XXX*(2), 45–53.

Lehmann, H. (1960b). La terminologie classique du karst sous l'aspect critique de la morphologie climatique moderne. *Revue de géographie de Lyon*, *35*(1), 1–6. https://doi.org/10.3406/geoca.1960.2377

Lehmann, H. (1968). Disskusionbemerkuagen zu "Physiographie and geological control in development of Cuban Mogotes" von V. Panos and O. Stelel. *Zeistschrift für Geomorphologie*, *12*, 171–173.

Lehmann, H., Krömmelbein, K., & Lötschert, W. (1956). Karstmorphologische, Geologische und Botanische studien in der Sierra de los Organos auf Cuba. *Erdkunde*, *10*(3), 185–204. https://doi.org/10.3112/erdkunde.1956.03.02

Lilienberg, D. A. (1984). Recent geodynamics of the Sierra Maestra and of the multi-purpose test area in Santiago de Cuba. In Nauka & Moscú (Eds.), *Polígonos Geodinámicos Complejos* (pp. 128–135). Editorial Nauka.

Linares, E., Osadchiy, P. G., Dovbnia, A. V., Gil, S., García, D., Zuazo, A., González, R., Bello, V., Brito, A., Bush, W. A., Cabrera, M., Capote, C., Cobiella, J. L., Díaz de Villalvilla, L., Eguipko, O. I., Evdokimov, Y. B., Fonseca, E., Ferrazola, G., Hernández, J., … Zelepuguin, V. N. (1985). *Mapa Geológico de la Republica de Cuba. E, 1, 500000.* Memoria del Instituto de Investigaciones Científicas de Geología "A. P. Karpinskiy" (VSEGEI) (pp. 1–2). Leningrado, URSS.

Lisiecki, L., & Raymo, M. (2005). A Pliocene – Pleistocene stack of 57 globally distributed benthic d18O records. *Paleoceanography*, *20*, 1–17.

López Rodríguez, R. (2009). El Geoparque Guaniguanico Guanahacabibes: Un Modelo para la conservación de la geodiversidad en Pinar del Río, Cuba, Informe técnico. *Ecovida*, *Inédito*, 1–37.

Magaz García, A. (1984). Análisis de una estructura neotectónica por métodos morfoestructurales en el SW de Pinar del Río, Cuba. *Ciencias de la tierra y del Espacio*, *8*, 29–45.

Magaz-García, A. (2021). Morfoestructúras. Tercera parte. Vías de clasificación y caracterización. Cuadernos de Geomorfología de Cuba. *Cuba Geográfica*, *1*, 1–32.

Martínez, D. (1994). *Informe sobre la generalización del mapa geológica del occidente de Cuba a escala 1:100000*. O.T.R.M. Pinar del Río.

Martínez, D., Fernández de Lara, R., Peláez, R., Vázquez, M., Hernández, J., Chang, J. C., Denis, R., & Cofiño, C. E. (1988). *Informe de Levantamiento Geológico y Búsquedas acompañantes a escala 1: 50000 en la parte central de la provincia de Pinar del Río*. ONRM.

Moleiro-León, L. F. (2003). Hidrogeología y Geomorfología Cárstica de Valle Ancón, Pinar de Río, Cuba. *Ingeniería hidraúlica y ambiental*, *24*(3), 3–9.

Molerio-León, L. F. (2006). *Los Mogotes del Valle de Viñales*. Monumento Nacional.

Molerio-León, L. F. (2021). El Factor Hidráulico en la identificación de "Niveles de Cavernamiento"en cuevas transfluentes: un tema no considerado. Cuadernos de Geomorfología de Cuba. *Cuba Geográfica*, *2*, 1–46.

Molerio-León, L. F., & Flores, E. (1997). Paleoclimas y Paleocarsos: los niveles de cavernamiento y la variabilidad del clima tropical en el golfo de Mexico y El Caribe. In D. M. Arellano, M. A. Gómez-Martín, & I. Atiguedad (Eds.), *Memoria Investigaciones hidrogeológicas en Cuba* (pp. 235–230).

Molerio-León, L., Guerra, M., Rocamora, E., & Pajón, J. (1999). Capítulo 4 Caracterización de los niveles de cavernamiento del karst de Cuba Occidental y su relación con las oscilaciones del nivel del mar durante el Cuaternario. In: *Monografía "Proyecto Paleoclima del Cuaternario Cubano: una caracterización cuantitativa. Banco de Proyectos del Programa Nacional de Cambios Globales y la Evolución del Medio Ambiente Cubano* (pp. 113–170).

Novo, R., Quintana, A. J., Hernández, M., González, I., Del Llano, R., Carmenate, H., & Hernández, P. (2005). Estudio preliminar de los niveles de cavernamiento del sistema subterráneo Guasasa. In *Memorias Congreso 65 Aniversario Sociedad Espeleológica de Cuba* (pp. 1–7).

Ortega, F., & Acevedo, M. (1987). La evolución de los suelos de Cuba durante el Cuaternario. *Ciencias de la Tierra y del Espacio*, *14*, 151–157.

Otero-Collazo, V., González-Ramón, A., Valdés-Ramos, J. J., Pajón-Morejón, J. M., Alons-Martínez, M., Cháves-Bonor, O., Sluka, M., Garcia-Pulpeiro, G., & Pou-Royo, A. (2016). Aspectos geomorfológicos del sistema cavernario Majaguas-Cantera. Campañas de exploración y topografía 2012–2016 (Pinar del Río, Cuba occidental). In B. Andreo, & J. J. Durán (Eds.), *El karst y el hombre: las cuevas como Patrimonio Mundial* (pp. 407–422). Asociación de Cuewvas Turísticas Españolas.

Peñalver, L., Cabrera, M., Trujillo, H., Morales, H., Pérez Lazo, J., Fundora, M., Molerio, L., Guerra, M., & Pedroso, I. (2001). Mapa de dexpósitos cuaternarios del archipiélago cubano a escala 1: 250000. In *IV Congreso de Geología y Minería. Geología del Cuaternario, Geomorfología y Carso* (pp. 94–103).

Peñalver, L., Denis, R., Martín, D., Núñez, A., & Rodríguez, L. (2022). Dos siglos de investigaciones sobre la Geología del Cuaternario en Cuba. *Geoinformativa*, *15*(1), 4–20.

Pérez Gil, W. (2010). *Estudio de un corte del Cretácico Temprano (Berriasiano Superior-Valanginiano Inferior), en el Miembro Tumbitas de la Formación Guasasa, Sierra del Infierno, Sierra de los Órganos, Cuba Occidental* [Tesis de ingeniero geólogo]. Departamento de Geología, Universidad de Pinar del Río.

Pszczolkowski, A., Piotrowska, K., Myczyunski, R., Skupinski, A., Grodzicki, J., Danilenwski, D., & Haczewski, G. (1975). Texto explicativo al mapa geológico a escala 1:250000 de lo provincia de Pinar del Río. *Informe I. G*, P., A.C.C., Oficina Nacional de Recursos Minerales, MINBAS (inedito).

Pszczolkowski, A., Pistrowska, K., Piotrowski, J., De la Torre, A., Myczolkownski, & A., Haczewski (1982). Contribución a la Geología de la Provincia de Pinar del Río. Editorial Científico – Técnica. La Habana. pp. 1–225. (Original work published 1987)

Pusharowski, Y.Y., Knipper, A.L., Puig-Rifa, M. (1996). *Mapa tectónico de Cuba (E: 1:250000)*. Academia de Ciencias de Cuba y Academia de Ciencias de la Unión Soviética. (original de 1967)

Pushcharovki, Y., Borkowska, M., Hamor, G., Suarez, J., & Velinov, I. (Eds.). (1985). *Mapa geológico de Cuba a Escala 1:250000*. Academia de Ciencias de Cuba, Instituto de Geología y Paleontología. Editor: Instituto de Geología de la Academia de Ciencias de la URSS.

Pushcharovski, Y. (1988). *Mapa Geológico de la República de Cuba escala 1: 250000*. Moscú.

Pushcharovski, Y., Knipper, A., & Puig-Rifa, M. (1967). *Mapa Tectónico de Cuba, escala 1: 500000*. AC. URSS.

Rojas, R., García Delgado, D., & Diaz, C. (2007). Guía de las localidades de los depósitos del límite Cretácico-Terciario en la región occidental de Cuba. In R. Rojas Consuegra, & K. Núñez-Cambra (Eds.), *Excursión a los depósitos del límite Cretácico-Terciario en Cuba occidental* pp. 1–25. Instituto de Geología y Paleontología. Museo NacionalHistoria Natural.

Shackleton, N. J. (1995). New data on the evolution of Pliocene climatic variability. In E. S. Vrba, G. H. Denton, T. C. Partridge, & L. H. Burckle (Eds.), *Paleocolcimate and Evolution with Emphasis on Human Origins* (pp. 242–248). Yale University Press.

Shein, V. S., Kleshev, K. A., Iparraguirre, J. L., García, E., Rodríguez, R., López, J. G., Socorro, R., & López, J. O. (1985). *Mapa Tectónico de la República de Cuba Escala 1; 500000*. Edición ICGC.

Tada, R., Nakano, Y., Iturralde-Vinent, M., Yamamoto, S., Kamata, T., Tajika, E., Toyoda, K., Kiyokawa, S., Garcia Delgado, D., Oji, T., Goto, K., Takayama, H., Rojas, R., & Matsui, T. (2002). Complex tsunami waves suggested by the Cretaceous-Tertiary boundary deposit at the Moncada section, western Cuba. In C. Koeberl, & K. G. MacLeod (Eds.), *Catastrophic Events and Mass Extinctions: Impacts and Beyond: Boulder, Colorado, Geological Society of America Special Paper* (Vol. 356, pp. 109–123).

Vázquez Torres, M. (Coordinador). (2017). Descripción y Fichas de los Lugares de InterésGeológico del Parque Nacional Viñales, para su propuesta como Geoparque (UNESCO). 125 p (inedito).

Vázquez Torres, M., Martínez Rius, A., Rodríguez Fernández, R., Gutiérrez, R. M., & Castellanos Abella, E. (2021). Parque Nacional Viñales (Cuba). Guía Geológica (Rodríguez, R. and Castellanos, E. Edits). Instituto Geológico y Minero de España (IGME), Ministerio de Energía y Minas de Cuba (MINEM). 204p.

Vázquez Torres, M., Pino Tonga, R., Hernández Mesa, Y., Ramírez Hernández, C., & Núñez Mantilla, H. (2000a). Mapa Geológico de la República de Cuba a E. 1: 50000. Minas de Matahambre (3483-IV). Empresa Geominera de Pinar del Río y Instituto de Geología y Paleontología. 168p.

Vázquez Torres, M., Pino Tonga, R., Hernández Mesa, Y., Ramírez Hernández, C., & Núñez Mantilla, H. (2000b). Mapa Geológico de la República de Cuba a E. 1: 50000. Consolación del Sur (3483-I). Empresa Geominera de Pinar del Río y Instituto de Geología y Paleontología. 184p.

Vázquez Torres, M., Pino Tonga, R., Hernández Mesa, Y., Ramírez Hernández, C., Núñez Mantilla, H., Álvarez, M., Estrada, V., Artiles, J., & Leyva, E. (2020). Mapa Geológico de la República de Cuba a E. 1: 50000. Cayo Inés de Soto (3484-III). Empresa Geominera de Pinar del Río y Instituto de Geología y Paleontología. 106pp.

Vázquez Torres, M., Robaina Iglesias, A., Díaz Guanche, C., Sánchez Carrillo, M. A., Martínez Serrano, Y., & Izquierdo Martínez, O. (2019). Valor del patrimonio geológico, proyecto Geoparque Viñales. Metodología para la selección de los geositios. *ECOVIDA*, *9*(2), 266–284.