REVISTA MEXICANA DE CIENCIAS GEOLÓGICAS

Revista Mexicana de Ciencias Geológicas, v. 42, num. 3, December 2025
ISSN-L 2007-2902
https://rmcg.unam.mx

Type: Supplementary material

OPEN ACCESS

SUPPLEMENTARY MATERIAL

for the paper

Geological heritage assessment in the central coast of Sonora and Midriff Islands region of the Gulf of California (Mexico): inventory and implications for management

by:
Jorge Alberto Miros-Gómez[1,*], Carles Canet[2], and Thierry Calmus[3]

Published in
Revista Mexicana de Ciencias Geológicas, 42(3), December 2025, p. 198–213
DOI: https://dx.doi.org/10.22201/igc.20072902e.2025.3.1896

Table S1. Summary of percentage weights assigned to each criterion according to value category and/or potential use (scientific, educational, and touristic).

Evaluation Criteria	Scientific (%)	Educational (%)	Touristic (%)
Representativeness (R)	30		
Key locality (L)	20		
Scientific knowledge (K)	5		
Integrity (C)	15		
Rarity (Ra)	15		
Geodiversity (Ga)	5	10	
Use limitations (U)	10	5	5
Vulnerability (Vu)		10	10
Accessibility (Ac)		10	10
Safety conditions (Sf)		10	10
Logistics and infrastructure (Li)		5	5
Density of population (Pd)		5	5
Association with other values (Hr)		5	5
Scenery/aesthetic (B)		5	15
Uniqueness/ Relevance (Re)		5	10
Observation conditions (O)		10	5
Educational/didactic potential (Dp)		20	
Interpretative potential (Ip)			10
Socioeconomic level (Se)			5
Proximity of recreational areas (Zr)			5
Total	100	100	100

Table S2. Percentage weights assigned to each criterion. The classification of the resulting values (Low, Medium, and High) follows the ranges proposed by Brilha (2016), adapted to a 0–10 scale. Scores <5 are classified as Low, 5.1–7.5 as Medium, and >7.5 as High. See also Table S8.

Evaluation Criteria	Weight (%)
Deterioration of geological elements (A)	35
Proximity to areas/activities with potential to cause degradation (B)	20
Legal protection (C)	20
Accessibility (D)	15
Density of population (E)	10
Total	100

Table S3. Types of interests and their descriptions for the characterization of LIGs, modified from ASGMI (2018). Complementary interests that may be associated with geological heritage are also included.

Interest	Description
Stratigraphic	Type locality of a formation, column, or stratigraphic section. Chronostratigraphic and lithostratigraphic units. Facies records. Reference sites for specific events.
Paleontological	Fossils (direct and indirect remains), paleontological deposits, and type localities.
Tectonic–Structural	Tectonic structures (faults, folds, deformation features, among others) across multiple scales.
Petrological	Igneous and metamorphic outcrops (including volcanism). Lithologies, compositions, and textures.
Sedimentological	Sections with well-preserved sedimentary structures; contributions to the understanding of transport and depositional processes.
Mineralogical	Minerals, parageneses, crystallizations, structures or textures, type localities, and deposits.
Geomorphological	Landforms from erosional and depositional processes of diverse origin (glacial, periglacial, desert, karst, fluvial, coastal, volcanic, astrobleme, meteoritic, aeolian, etc.). Unusual morphologies and iconic geological landscapes.
Hydrogeological	Springs, seeps, hot springs, geysers, sinkholes, lagoons. Unique hydrochemical springs.
Collections/Museums	Museums and collections: major museums with minerals, rocks, fossils, and meteorites.
Geological history	Classic localities that, although not type localities, first illustrated key principles or were significant in the history of geosciences.
Industrial/Mining	Immovable structures linked to past and present mining (not part of natural geological heritage).
Pedological/ Edaphological	Type soil profile sections.
Complementary interests (Biological)	
Endemism	Presence and restricted distribution of species within a geographic area (islands or islets), influenced by geological conditions.
Feeding site	Sand bars, caves, or other features favoring feeding or resting areas for species.
Nesting and breeding site	Sand bars, caves, or other features favoring nesting and breeding areas.
Protected and migratory species	Species meeting the three previous criteria and listed under national and international protection (NOM-059; IUCN Red List; CITES).
Complementary interests (Cultural)	
Historical	Sites of historically significant events (regional, national, or international), including tangible forms such as monuments, churches, and villages.
Archaeological	Sites where, in addition to their geological interest, well-preserved archaeological remains are found.
Geosymbol	Geological places or features that form part of the identity and traditions (for spiritual or material reasons) of local communities.

RMCG | v. 42 | núm. 3 | www.rmcg.unam.mx | DOI: http://dx.doi.org/10.22201/igc.20072902e.2025.3.1896

Table S4. Assessment criteria and their descriptions, based on García-Cortés *et al.* (2014) and Brilha (2016). Note: * Indicates the criteria considered in the expert consultation.

Evaluation Criteria	Description
*Representativeness (R)	Capacity of a site to adequately illustrate geological elements or processes (related to the considered geological framework).
*Key locality (L)	Capacity of a site to serve as a stratigraphic, paleontological, or mineralogical reference within the considered geological framework.
*Scientific knowledge (K)	Refers to the geoscientific relevance and interest of the site, which make it the subject of publications and scientific studies (related to the considered geological framework).
*Integrity (C)	Related to the conservation status of the main geological elements (related to the considered geological framework).
*Rarity (Ra)	Refers to the scarcity, in terms of number, of sites with similar features within the study area and the considered geological framework.
*Geodiversity (Ga)	Indicates the presence of multiple features or processes of geological interest.
Use limitations (U)	Indicates the existence of physical obstacles and legal constraints on the use of the site.
Accessibility (Ac)	Linked to greater ease of access for visitors (higher potential for use), but proportional to a higher likelihood of vandalism or unintentional damage.
Vulnerability (Vu)	Indicates the presence of geological elements that may be damaged by visitors (influenced by the size of the element), thereby reducing their potential for use.
Safety conditions (Sf)	Indicates whether activities around the site can be carried out under low-risk conditions for visitors.
Logistics and infrastructure (Li)	Indicates the existence of facilities within a defined radius to accommodate visitors (lodging, restaurants, health centers, and mobile networks).
Density of population (Pd)	Linked to the number of inhabitants within a defined radius and the potential visitor carrying capacity, but proportional to a higher likelihood of vandalism or unintentional damage.
*Association with other values (Hr)	Indicates whether the site contains other non-geological elements of natural or cultural heritage, or is located in proximity to them, which may attract a greater number of visitors.
*Observation conditions/ Visibility (O)	Indicates the degree of ease provided by the surroundings to observe the site and its features.
* Scenery/aesthetic (B)	Indicates the aesthetic quality and scenic beauty of the site or geological feature.
*Uniqueness/Relevance (Re)	Indicates the distinctiveness and rarity of the geological feature at local/regional, national, or international levels, which may promote public interest in the site.
*Educational/didactic potential (Dp)	Indicates whether the site illustrates geological features or processes that can be explained to students at different educational levels, or if it is already used for this purpose.
*Interpretative potential (Ip)	Indicates how easily the site illustrates the importance or usefulness of geology to the general public (without prior geological knowledge).
Proximity of recreational areas (Zr)	Indicates the proximity of recreational or tourist areas to the site, linked to a higher potential number of visits but also proportional to a greater likelihood of vandalism.
Socioeconomic level (Se)	Indicates the income level of people living near the site, suggesting a higher probability of visitation.

Table S5. Indicators and parameters for the quantitative assessment of the scientific value of the LIGs, modified after García-Cortés *et al.* (2014) and Brilha (2016), with some indicators adapted to the local context.

Criterion/Indicators	Parameters
Representativeness (R)	
The geosite is the best example in the study area to illustrate elements or processes related to the considered geological framework (when applicable).	4
The geosite is a good example in the study area to illustrate elements or processes related to the considered geological framework (when applicable).	2
The geosite reasonably illustrates elements or processes in the study area, related to the considered geological framework (when applicable).	1
Key locality (L)	
The geosite is recognized as a GSSP or ASSP by the IUGS, or as an IMA reference site (or by another international association).	4
The geosite is a reference locality used by the international scientific community, directly related to the considered geological framework (when applicable).	2
The geosite is a reference locality used by the national scientific community, directly related to the considered geological framework (when applicable).	1
Scientific knowledge (K)	
There are PhD theses and articles in international scientific journals about this geosite, directly related to the considered geological framework (when applicable).	4
There are theses and articles in national scientific publications about this geosite, directly related to the considered geological framework (when applicable).	2
There are ongoing scientific studies, technical reports, and abstracts presented at national and international scientific events about this geosite, directly related to the considered geological framework (when applicable).	1
Integrity (C)	
The main geological elements related to the considered geological framework (when applicable) are very well preserved.	4
The geosite is not so well preserved, but the main geological elements related to the considered geological framework (when applicable) are still preserved.	2
The geosite with preservation problems, with the main geological elements (related to the considered geological framework, when applicable) significantly altered or modified.	1
Geodiversity (Ga)	
Geosite with more than three types of distinct geological features with scientific relevance.	4
Geosite with three types of distinct geological features with scientific relevance.	2
Geosite with two types of distinct geological features with scientific relevance.	1
Rarity (Ra)	
The geosite is the only occurrence of this type in the study area (representing the considered geological framework, when applicable).	4
In the study area, there are two or three examples of similar geosites (representing the considered geological framework, when applicable).	2
In the study area, there are four to five examples of similar geosites (representing the considered geological framework, when applicable).	1
Use limitations (U)	
The site has no limitations (permissions, physical barriers, etc.) for sampling/fieldwork.	4
It is possible to collect samples and carry out fieldwork after overcoming some limitations.	2
Sampling and fieldwork are very hard to conduct due to limitations that are difficult to overcome (legal permits, physical barriers, etc.).	1

RMCG | v. 42 | núm. 3 | www.rmcg.unam.mx | DOI: http://dx.doi.org/10.22201/igc.20072902e.2025.3.1896

Table S6. Combined indicators and parameters for the quantitative assessment of educational and touristic potentials, modified after García-Cortés *et al.* (2014) and Brilha (2016), with some indicators adapted to the local context.

Criterion/Indicators	Parameters
Vulnerability (Vu)	
The geological elements of the geosite present no possible deterioration by anthropic activity.	4
There is the possibility of deterioration of secondary geological elements by anthropic activity.	3
There is the possibility of deterioration of main geological elements by anthropic activity.	2
There is the possibility of deterioration of all geological elements by anthropic activity.	1
Accessibility (Ac)	
Site located less than 1 km from a paved road (accessible on foot or by bus via a dirt road).	4
Site located less than 3 km from a paved road (accessible on foot or by bus via a dirt road).	3
Site accessible only by vehicle, but via a dirt road (<20 km).	2
Site without direct road access, requiring rental or arrangement of special services (boats, guides, special equipment, etc.).	1
Use limitations (U)	
The site has no limitations to be used by students and tourists.	4
The site can be used by students and tourists but only occasionally	3
The site can be used by students and tourists but only after overcoming limitations (legal, permissions, physical, tides, floods, etc.)	2
The use by students and tourists is very hard to be accomplished due to limitations difficult to overcome (legal, permissions, physical, tides, floods, etc.)	1
Safety conditions (Sf)	
Site with safety facilities (fences, stairways, handrails, etc.), mobile phone coverage, and located less than 5 km from emergency services.	4
Site with safety facilities (fences, stairways, handrails, etc.), mobile phone coverage, and located less than 25 km from emergency services.	3
Site with no safety facilities, but with mobile phone coverage, and located less than 50 km from emergency services.	2
Site with no safety facilities, no mobile phone coverage, and located more than 50 km from emergency services.	1
Logistics and infrastructure (Li)	
Accommodation and restaurants for groups of 50 people less than 15 km away from the site.	4
Accommodation and restaurants for groups of 50 people less than 50 km away from the site.	3
Accommodation and restaurants for groups of 50 people less than 100 km away from the site.	2
Accommodation and restaurants for groups less than 25 people and less than 50 km away from the site.	1
Density of population (Pd)	
More than 1,000,000 inhabitants within a 100 km radius of the site.	4
Between 1,000,000 and 600,000 inhabitants within a 100 km radius of the site.	3
Between 600,000 and 200,000 inhabitants within a 100 km radius of the site.	2
Less than 200,000 inhabitants within a 100 km radius of the site.	1
Association with other values (Hr)	
Occurrence of several ecological and cultural values less than 5 km from the site.	4
Occurrence of several ecological and cultural values less than 10 km away from the site.	3
Occurrence of one ecological value and one cultural value less than 10 km away from the site.	2
Occurrence of one ecological or cultural value less than 10 km away from the site.	1
Scenery/aesthetic (B)	
Site currently used as a tourist destination in national campaigns.	4
Site occasionally used as a tourist destination in national campaigns.	3
Site currently used as a tourist destination in local campaigns.	2
Site occasionally used as a tourist destination in local campaigns.	1

continues

Table S6 (cont.). Combined indicators and parameters for the quantitative assessment of educational and touristic potentials, modified after García-Cortés *et al.* (2014) and Brilha (2016), with some indicators adapted to the local context.

Criterion/Indicators	Parameters
Uniqueness/Relevance (Re)	
The site shows unique and uncommon features considering this and neighboring countries.	4
The site shows unique and uncommon features in the country.	3
The site shows common features in this region, but they are uncommon in other regions of the country.	2
The site shows features rather common in the whole country.	1
Observation conditions/ Visibility (O)	
All geological elements can be observed in good condition.	4
There are some obstacles that make difficult the observation of some geological elements.	3
There are some obstacles that make difficult the observation of the main geological elements.	2
There are obstacles that significantly obstruct the observation of the main geological elements.	1

Table S7. Independent indicators and parameters for the quantitative assessment of educational and touristic potentials, modified after García-Cortés *et al.* (2014) and Brilha (2016), with some indicators adapted to the local context. Note: ENIGH–INEGI refers to the *Encuesta Nacional de Ingresos y Gastos de los Hogares - Instituto Nacional de Estadística y Geografía*.

Criterion/Indicators	**Parameters**
EDUCATIONAL USE	
Educational/didactic potential (Dp)	
The site presents geological elements that can be taught at all educational levels.	4
The site presents geological elements that can be taught in primary and secondary schools.	3
The site presents geological elements that can be taught in high schools (or equivalent).	2
The site presents geological elements that are taught only in higher education institutions (universities).	1
Geodiversity (Ga)	
More than 3 types of geodiversity elements occur in the site (mineralogical, palaeontological, geomorphological, etc.).	4
There are 3 types of geodiversity elements in the site.	3
There are 2 types of geodiversity elements in the site.	2
There is only 1 type of geodiversity element in the site.	1
TOURISTIC USE	
Interpretative potential (Ip)	
The site presents geological elements in a very clear and expressive way to all types of audiences.	4
The public needs to have some geological background to understand the geological elements of the site.	3
The public needs to have a solid geological background to understand the geological elements of the site.	2
The site presents geological elements only understandable to geological experts.	1
Socioeconomic level (Se)	
The site is located in a state with household income above the national average (ENIGH-INEGI).	4
The site is located in a state with household income similar to the national average (ENIGH-INEGI).	3
The site is located in a state with household income below the national average (ENIGH-INEGI).	2
The site is located in a municipality or locality with notable socioeconomic deterioration.	1
Proximity of recreational areas (Zr)	
The site is located less than 5 km away from a recreational area or tourist attraction.	4
The site is located less than 10 km away from a recreational area or tourist attraction.	3
The site is located less than 15 km away from a recreational area or tourist attraction.	2
The site is located less than 25 km away from a recreational area or tourist attraction.	1

RMCG | v. 42 | núm. 3 | www.rmcg.unam.mx | DOI: http://dx.doi.org/10.22201/igc.20072902e.2025.3.1896

Table S8. Criteria and their indicators for the assessment of degradation risk, modified after Brilha (2016), adapted in this study to fit the context of the study area. See the description of the criteria in the cited reference.

Criterion/Indicators	Parameters
Deterioration of geological elements	
Possibility of deterioration of all geological elements.	4
Possibility of deterioration of the main geological elements.	3
Possibility of deterioration of secondary geological elements.	2
Minor possibility of deterioration of secondary geological elements.	1
Proximity to areas/activities with potential to cause degradation	
Site located less than 100 m from a potentially degrading area/activity.	4
Site located less than 500 m from a potentially degrading area/activity.	3
Site located less than 1 km from a potentially degrading area/activity.	2
Site located less than 2 km from a potentially degrading area/activity.	1
Legal protection	
Site located in an area with no legal protection and no control of access.	4
Site located in an area with no legal protection but with control of access.	3
Site located in an area with legal protection but no control of access.	2
Site located in an area with legal protection and control of access.	1
Accessibility	
Site located less than 1 km from a paved road (accessible on foot or by bus via a dirt road).	4
Site located less than 3 km from a paved road (accessible on foot or by bus via a dirt road).	3
Site accessible only by vehicle, but via a dirt road (<20 km).	2
Site without direct road access, requiring rental or arrangement of special services (boats, guides, special equipment, etc.).	1
Density of population	
More than 1000000 inhabitants within a 100 km radius of the site.	4
Between 1000000 and 600000 inhabitants within a 100 km radius of the site.	3
Between 600000 and 200000 inhabitants within a 100 km radius of the site.	2
Less than 200000 inhabitants within a 100 km radius of the site.	1

Table S9. Description of the LIGs identified in this study (see description of groups in the manuscript text).

LIG	General description
RP-LIG1 Roof pendant of Isla Dátil (Hastaacoj)	Pre-Cenozoic basement. Exceptional exposure of Paleozoic deep-marine metasediments intruded by Cretaceous granitic plutons (roof pendant), where the metasedimentary rocks preserve Ordovician graptolites and record the tectonic evolution of Laurentia and Gondwana during the assembly of Pangea. The granitic pluton, in turn, records the magmatic activity that took place in the Cretaceous, when a subduction-related margin existed along northwestern Mexico and the southwestern United States.
RP-LIG2 Rocks and geomorphology of Isla Cholludo (Hastisil)	Pre-Cenozoic basement. Small island composed of Paleozoic metasedimentary rocks correlated with those from Isla Dátil and the southern part of Isla Tiburón. Its steep cliffs and incipient sea stack, together with dense *Pachycereus pringlei* vegetation, highlight the interplay between geology-geomorphology, and biodiversity.
HM-LIG3 "Mine" of Cerro Peineta (Hasteemla)	Pre-Cenozoic basement. Skarn-type deposit formed by the interaction between hydrothermal fluids and Paleozoic or Jurassic sedimentary rocks during Cretaceous plutonism. Although small and no longer exploited, it represents the only identified deposit of its kind in the area, highlighting hydrothermal processes and magmatic evolution. The site also offers panoramic views toward the Sierra Seri mountains and holds cultural significance for the Comcaac community.
VF-LIG4 Structures and tuff of Cerro Kino (Hasteecöla)	Group II: Early–Middle Miocene arc volcanic rocks. Volcanic and sedimentary sequence of Miocene age affected by faulting along the coastal Sonora fault zone. The rocks are tilted up to 80° eastward, and the peaks are composed of the ~12.5 Ma tuff of San Felipe, a widespread ignimbrite that serves as a tectonic marker for Proto–Gulf reconstruction, linking coastal Sonora and the eastern coast of Baja California during Miocene volcanism. The site also stands out for its striking geomorphology, with rock cavities, some of which are associated with archaeological evidence.
VF-LIG5 Structures and rocks of cerro San Ignacio (Ixpan it)	Group II: Early–Middle Miocene arc volcanic rocks. Promontory exposing a moderately dipping normal fault (36° SE), which juxtaposes Miocene andesitic pyroclastic breccias over tonalites of the coastal Sonora batholith. The site illustrates intrusive and tectonic processes within a single outcrop and displays diverse geomorphological features such as rock shelters, sea cliffs, and intertidal platforms with tide pools, making it an ideal site for educational activities linking geology and marine sciences.
VF-LIG6 Rocks and geomorphology of Isla Alcatraz (Soosni)	Group II: Early–Middle Miocene arc volcanic rocks. Island composed of Miocene pyroclastic breccias associated with volcanic activity during the final stage of Farallon plate subduction beneath North America. Flat areas consist of younger Quaternary marine deposits that record coastal dynamics and sea-level changes. Steep cliffs on the western and southern margins display rock shelters and pareidolic forms that enhance the site's scenic and cultural value. These cliffs also serve as resting and nesting areas for seabirds and marine mammals.
VF-LIG7 Fault structures on cliffs of Isla Tiburón	Pre-Cenozoic basement and Group II: Early–Middle Miocene arc volcanic rocks. Coastal section displaying several normal faults, including the Hihitiij fault and the main fault exposed at Hehe Hasoaaj Quih An Ihiip Iyat (Punta Amarilla) cliff. The Hihitiij normal fault juxtaposes Miocene volcanic–sedimentary rocks over Paleozoic metasediments, with fault planes showing slickenlines that indicate the direction of movement. At Punta Amarilla, the fault offsets Miocene volcanic layers, including a vesicular basalt horizon whose material has been partially incorporated into the fault plane, providing clear evidence of normal fault displacement. Nearby cliffs display flow banding in rhyolitic lavas and a contrasting vitrophyric layer at their base, enhancing the site's aesthetic and educational value.
VF-LIG8 Paleovalley of Punta Colorada and Hipat Mesa (Hast Hinamj & Hipat)	Group II and Group III volcanic and sedimentary rocks. Ancient tectonic valley (paleovalley) preserving a detailed record of the early rift activity of the Gulf of California. At its base, basaltic lavas (>15 Ma) show gentle folding and tilting, forming part of the down-dropped block of the Colorado fault. These lavas are overlain by nearly horizontal sedimentary rocks interbedded with the 12.5 Ma tuff of San Felipe, while a Pliocene dacitic volcanic deposit caps the sequence, forming the prominent peak of Hast Hinamj. To the northwest, the subhorizontal deposits of Hipat Mesa consist of ~4.4 Ma ash and pumice beds that overlie the inactive La Cruz fault, constraining the end of local tectonic activity. This paleovalley provides key evidence for reconstructing regional fault displacement, and it has been inferred that the tuff of San Felipe in this area could correlate with equivalent deposits now exposed on Isla Ángel de la Guarda, close to each other prior to their lateral displacement along the Tiburón transform fault.
VF-LIG9 Tuff of Punta Reina (Hast Heepni)	Group II and Group III volcanic rocks. Coastal cliffs exposing an exceptional record of pyroclastic deposits formed during major eruptions at ~12.6 and ~6.3 Ma, corresponding to the tuff of San Felipe and the tuff of Mesa Cuadrada, respectively. These ignimbrites are correlated with volcanic units of the Puertecitos Volcanic Province in Baja California, indicating that both margins were once connected before the Gulf of California opened (conjugate margins). The stratigraphic succession in other parts of the area, including the tuffs of Dead Battery Canyon and Arroyo El Canelo (~6.1 Ma), records the onset of crustal displacement and the transition to the modern Gulf of California. Studies at this site provided the basis for estimating more than 250 km of right-lateral offset over the past 6 Ma, marking the establishment of the Pacific–North America plate boundary.
CM-LIG10 Marine basin of southwestern Isla Tiburón (Hast Pizal It)	Group III and Group IV volcanic and marine sedimentary rocks. The southwestern marine basin of Isla Tiburón (SWIT) preserves the only exposed Miocene marine sequence on the eastern margin of the northern Gulf of California within North American continental crust (see also VP-LIG11). Initially interpreted as Middle Miocene (15–11 Ma), this sequence is a Late Miocene in age (~6.2 Ma), coinciding with the major marine incursion that reached the northern Gulf. The basin, shaped by oblique motion along the La Cruz fault, preserves Gilbert-type delta deposits containing marine fossils that record the transition to marine conditions. Once misinterpreted, the site now provides crucial evidence that reshaped understanding of the northern Gulf's geological evolution and represents an internationally significant geoheritage locality.

continues

RMCG | v. 42 | núm. 3 | www.rmcg.unam.mx | DOI: http://dx.doi.org/10.22201/igc.20072902e.2025.3.1896

Table S9 (cont.). Description of the LIGs identified in this study (see description of groups in the manuscript text).

LIG	General description
VP-LIG11 Volcanic rocks and cliffs of Isla San Esteban (Cofteecöl)	Group IV volcanic rocks and marine sedimentary rocks. Isla San Esteban is composed of andesitic and dacitic lavas, rhyolitic domes, pyroclastic deposits, and fossiliferous marine sediments, all formed between ~4.5 and 2.5 Ma. These volcanic rocks record a period of intense crustal extension linked to the opening of the Gulf of California, but their geochemical signatures reveal the coexistence of both calc-alkaline and adakitic magmas. The presence of adakitic compositions suggests partial melting of subducted oceanic slab remnants of the ancient Farallon plate, thermally reactivated during crustal thinning. The coexistence of these magmas makes Isla San Esteban a key site for understanding the transition from subduction-related to rift-related magmatism in the northern Gulf. Correlations of fossiliferous marine sediments with the SWIT marine basin further indicate a shared history of Pliocene marine incursions and rifting.
PC-LIG12 Marine terraces and paleontological record of the San Nicolás area (Hacac)	Quaternary deposits and landforms. These terraces are exposed ancient coastal platforms composed of highly fossiliferous Pleistocene marine deposits overlain by Holocene alluvial and aeolian sediments. These layers were deposited during the last interglacial (MIS 5e, ~125 ka). The nearly horizontal and laterally continuous strata, together with those of other nearby localities, indicate vertical stability of the eastern Gulf margin, contrasting with other uplifted terraces in Baja California. The site is associated with small coves, pocket beaches, and intertidal rocky zones developed on granitic outcrops of the coastal Sonora batholith.
PC-LIG13 Marine terraces and paleontological record of Punta Chueca (Socaaix)	Quaternary deposits and landforms. These terraces are coastal landforms that extend for ~2 km between Punta Chueca and Punta Onah, they are the highest marine terraces in the study area, with steep slopes up to ~9 m that gradually decrease toward the Punta Onah wetland. The sequence includes fossiliferous marine deposits (coquina) formed under low- to moderate-energy conditions, corresponding to the last interglacial (substage MIS 5e, ~125 ka). Luminescence dating (Ln/Tn) on sandy sediments yielded ages between 118 and 148 ka, confirming correlation with MIS 5e. The gentle tilting of strata suggests minor tectonic uplift likely associated with local faulting, possibly linked to an inferred NNW–SSE fault crossing the Infiernillo Channel.
PC-LIG14 La Cruz coastal lagoon (Xojtis Xtaasi)	Quaternary deposits and landforms. Coastal lagoon of probable mixed origin, likely formed during the Holocene transgression that flooded former fluvial valleys and later became enclosed by sandy spits shaped by littoral drift. It includes diverse environments such as mudflats, tidal channels, mangroves, and evaporitic flats. Sediment distribution reflects decreasing energy toward the inner lagoon, while paleoenvironmental evidence suggests alternating brackish and marine phases since the Little Ice Age. Designated as a Ramsar Site, it hosts a wide range of scientific studies and conservation efforts.
PC-LIG15 El Sargento lagoon complex (Zaaj Cheel) and Cerro Tepopa	Quaternary deposits and landforms. Punta Tepopa marks the northern limit of the Infiernillo Channel and represents one of the most characteristic LIGs in the study area. The landscape includes the Sierra Seri to the east, the isolated Cerro Tepopa to the west—formed by a tonalite–diorite pluton of the Coastal Sonora Batholith—and an arid closed basin composed of alluvial fans and playas. The El Sargento lagoon, the largest in the channel, is enclosed by a sandy spit and a tombolo that protect a system of tidal channels, mangroves, and sand banks. Geological evidence indicates repeated coastal changes since the last interglacial (MIS 5e, ~125 ka), when higher sea levels flooded coastal plains, forming shallow marine and lagoonal environments preserved today in marine sedimentary deposits around Punta Tepopa.
PC-LIG16 Estero Santa Rosa (It Xtaasi)	Quaternary deposits and landforms. Coastal lagoon classified as a cuspate foreland, formed by the convergence of two sandy spits advancing in opposite directions. These spits developed independently on convex coastal projections associated with the lower limit of alluvial fans and likely over Pleistocene marine deposits correlated with the MIS 5e highstand (~125 ka). The southern spit is broader and more developed, indicating dominant south-to-north littoral drift, while the northern one is narrower and shows successive accretional ridges. Their convergence enclosed a lagoon now occupied by mangroves (*Rhizophora mangle, Avicennia germinans*) and tidal channels.
PC-LIG17 Estero-Punta San Miguel (Hanc Xtaasi)	Quaternary deposits and landforms. Coastal lagoon formed by the growth of a single curved (cuspate) spit, composed mainly of coarse sands and gravels derived from andesite, tuff, and vitrophyric rocks. The narrow spit (<50 m wide) extends in three successive segments: an initial NNE–NE-oriented reach (~3 km), a shorter NW-directed section, and a final recurved SW hook-shaped tip. Its development is driven by seasonal winds and wave action characteristic of the Infiernillo Channel, with the distal curvature reflecting the combined effects of longshore drift and wave diffraction.
PC-LIG18 Estero-Punta Tormenta (Xeefe Xtaasi)	Quaternary deposits and landforms. Complex coastal landform formed by overlapping sandy spits developed on headlands associated with Pleistocene marine terraces of the last interglacial (MIS 5e, ~125 ka). The main V-shaped spit extends southeastward and then curves southwest, while a younger southeast-oriented spit merges with another from the south (~1.1 km long), reflecting opposing longshore drift directions. The enclosed low-energy lagoon hosts tidal channels and mangrove patches, although its natural dynamics appear to have been partially altered by human modifications such as access roads and a small landing strip.
PC-LIG19 Estero-Punta Hoona (Xtaasi It)	Quaternary deposits and landforms. Cuspate foreland with a triangular outline ending in a small southwest-oriented hook. A small coastal lagoon with mangroves lies at the northern base of the landform, connected to the sea by narrow channels across the main sandy ridge. Low dunes and vegetated sandy crests characterize the central and southern sectors. The foreland developed gradually under the influence of northwesterly waves that transported and deposited sand along the coast, later modified by seasonal longshore drift from the south that shaped its curved southern margin.

continues

Table S9 (cont.). Description of the LIGs identified in this study (see description of groups in the manuscript text).

LIG	General description
PC-LIG20 Estero-Punta Víboras (Ziipxöl Iifa Xtaasi)	Quaternary deposits and landforms. Cuspate coastal spit forming a triangular V-shaped landform enclosing a small lagoon with mangroves and tidal channels. The narrow southern ridge represents the initial growth stage, developed by littoral drift transporting sediments from the southeast to the northwest and favored by a natural inflection of the coastline. Subsequent northward progradation and wave refraction from the north reshaped the feature into its current "V" configuration, with wider parallel ridges and dunes marking successive accretion stages.
PC-LIG21 Estero-Punta Arenas (Tacseen Xtaasi)	Quaternary deposits and landforms. Cuspate foreland formed by the convergence of two sandy spits shaped by opposing longshore currents. The larger north–south-oriented spit displays successive dune ridges and recurved sandy tongues that record multiple accretion and stabilization phases, while the smaller west-oriented spit preserves internal accretion ridges. As both spits gradually extended and merged, they enclosed a broad coastal lagoon with mangroves, tidal channels, and sand bars. The main lagoon inlet lies at the junction of the spits, where one forms a distinctive hook-shaped feature.
PC-LIG22 Punta Larga (Zozni Iyat)	Quaternary deposits and landforms. Coastal complex composed of three cuspate forelands at different developmental stages. The southern foreland retains a clear V-shape and encloses a mangrove lagoon, while the central and northern features show progressive infilling and stabilization, preserving relics of former coastal lagoons. These forelands are associated with extensive sandy shallows and small linear wetlands that are rarely visited by local communities.
PC-LIG23 Estero-Punta Perla (Xtaasi Quih An Cmasol)	Quaternary deposits and landforms. Coastal system composed of two interconnected landforms at different evolutionary stages: the Laguna Mala lagoon and the Punta Perla spit. Laguna Mala developed between two converging sandy spits shaped by opposing littoral drifts, forming a protected mangrove lagoon. Punta Perla, originally ~4 km long, represents the main coastal spit of this site, formed by the combined action of waves, tides, and wind. Its inner side has allowed the expansion of mangrove habitats within the coastal lagoon, illustrating a highly dynamic coastal system.
PG-LIG24 Anchored dunes of San Nicolás	Quaternary deposits and landforms. Anchored dune system developed during the Holocene together with the coastal plains south of Cerro San Nicolás. The dunes formed as wind-blown sands accumulated against the granitic outcrop of the coastal Sonora batholith (part of Cerro San Nicolás), which acts as a natural obstacle where the sands are trapped and deposited. Seasonal winds continuously reshape the dunes, producing a combination of stabilized vegetated ramps and stepped active ridges. The fine quartz-rich sands ultimately originate from the same granitic rocks of the batholith, but their provenance is indirect, as they were reworked from older deposits exposed during lower sea-level periods.

RMCG | v. 42 | núm. 3 | www.rmcg.unam.mx | DOI: http://dx.doi.org/10.22201/igc.20072902e.2025.3.1896