

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

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ABSTRACT

This study presents an interdisciplinary effort to show how geological knowledge can inform conservation and sustainable development in northwestern Mexico. A geoheritage inventory and assessment were conducted along the central coast of Sonora and part of the Midriff Islands in the Gulf of California to support the integration of places of geological interest or geosites into local conservation frameworks. The adapted methodology combined quantitative and qualitative criteria to evaluate the scientific, educational, and touristic value of sites, as well as their degradation risk. Twenty-four places of geological interest were identified, recording key events in the region's geological evolution, with levels of relevance ranging from local to international. Eight sites show high scientific value, twelve have strong educational potential, and six offer opportunities for geotourism. Additionally, twelve sites face medium-to-high threats due to unregulated tourism, land-use change, and limited institutional protection. Two broad management strategies were identified: (1) sites lacking formal protection, often located in ecologically valuable areas but without active management, and (2) sites within legal frameworks, such as protected areas, Ramsar sites within Indigenous territories, that benefit from some conservation but lack formal geoheritage recognition. Tailored strategies are proposed for each group, including integration into land-use plans, regulatory updates, stakeholder engagement, community-based geotourism, and educational outreach programs; however, these proposals require further validation. The results highlight the intersection of geological, biological, and cultural values—especially in Indigenous territories—and underscore the potential of geoheritage as a basis for integrated conservation. While the area could aspire to future international designations, such as a UNESCO Global Geopark, current priorities call for raising awareness on geoheritage sites and strengthening community participation. Overall, this work shows that geoconservation remains a pending task in regional conservation agendas, and that geological knowledge can contribute meaningfully to the design of locally grounded, socially inclusive management and sustainable use strategies.

Keywords: geoconservation; inventory; geoheritage; geosites; geodiversity; management; Sonora; Midriff Islands; Gulf of California; Mexico.

RESUMEN

Este estudio presenta un esfuerzo interdisciplinario que muestra cómo el conocimiento geológico puede orientar la conservación y el desarrollo sostenible en el noroeste de México. Se llevó a cabo

un inventario y una valoración del patrimonio geológico a lo largo de la costa central de Sonora y parte de las Grandes Islas del Golfo de California, con el fin de fomentar la integración de lugares de interés geológico o geositios en los marcos locales de conservación. La metodología adaptada combinó criterios cuantitativos y cualitativos para evaluar el valor científico, educativo y turístico de los sitios, así como su respectivo riesgo de degradación. Se identificaron veinticuatro lugares de interés geológico que registran eventos clave en la evolución geológica de la región, con una relevancia que va desde el ámbito local hasta el internacional. Ocho sitios muestran alto valor científico, doce tienen un fuerte potencial educativo y seis ofrecen oportunidades para el geoturismo. Además, doce de ellos enfrentan amenazas medias a altas debido al turismo no regulado, el cambio de uso de suelo y la escasa protección institucional. Se identificaron dos estrategias generales de gestión para estos lugares: (1) sitios sin protección formal, a menudo ubicados en áreas ecológicamente valiosas, pero sin manejo activo, y (2) sitios dentro de marcos legales, como áreas protegidas, sitios Ramsar dentro de territorios indígenas, que se benefician de ciertas medidas de conservación, pero carecen de reconocimiento formal como patrimonio geológico. Se proponen estrategias específicas para cada grupo, que incluyen su integración en planes de ordenamiento territorial, actualización normativa, participación de actores locales, geoturismo comunitario y programas de educación y divulgación; no obstante, estas propuestas requerirán una validación adicional. Los resultados destacan la intersección entre valores geológicos, biológicos y culturales—especialmente en territorios indígenas—y subrayan el potencial del patrimonio geológico como base para una conservación integrada. Si bien el área podría aspirar en el futuro a designaciones internacionales, como un Geoparque Mundial de la UNESCO, las prioridades actuales exigen primero la sensibilización sobre la importancia del patrimonio geológico y fortalecer la participación comunitaria. En conjunto, este trabajo muestra que la geoconservación sigue siendo una tarea pendiente en las agendas regionales de conservación, y que el conocimiento geológico puede contribuir significativamente al diseño de estrategias de manejo y uso sostenible fundamentadas en el contexto local y con participación social activa.

Palabras clave: geoconservación; inventario; patrimonio geológico; geositios; geodiversidad; manejo; Sonora; Grandes Islas; Golfo de California; México.

INTRODUCTION

The Gulf of California is one of the most tectonically active and geologically significant regions in northwestern Mexico. As a young and evolving oblique rift system, it has long attracted the attention of the international geoscientific community. Its evolution provides a natural laboratory for understanding geodynamic, magmatic, and paleogeographic processes associated with continental break-up and ocean basin formation.

This scientific relevance has led to sustained national and international research efforts over the past five decades (e.g., Gastil *et al.*, 1975; Gastil & Krummenacher, 1977), which have produced a robust body of knowledge on the region's tectonic evolution, magmatism, and sedimentary environments (e.g., Poole *et al.*, 2005; Aragón-Arreola & Martín-Barajas, 2007; Fletcher *et al.*, 2007; Bennett & Oskin, 2014; Umhoefer *et al.*, 2018).

Within this context, the central coast of Sonora and the Midriff Islands region—encompassing Isla San Esteban, Isla Tiburón, Bahía de Kino, and the Comcaac territory—stand out as a natural laboratory where lithological, geomorphological, and structural diversity converge within a relatively small area (Miro-Gómez *et al.*, 2024). This geodiversity has been well documented in geological literature, highlighting its scientific value and relevance for understanding the opening of the Gulf of California and related geodynamic processes (e.g., Oskin and Stock, 2003a; Bennett *et al.*, 2013, 2016).

Despite this long-standing tradition of geological research, geodiversity and geological heritage remains largely excluded from conservation and territorial management strategies in the region. While biological and cultural values have guided conservation and sustainable development initiatives, the geological dimension remains

marginal, despite its intrinsic value and its role in shaping both the landscape and distribution of biotic communities.

This study seeks to contribute to the valuation of geological heritage in the central Sonoran coast and Midriff Islands region by identifying, inventorying, and assessing places of geological interest. It aims to highlight the scientific, educational, tourist, and cultural values of these places, and to inform future efforts to integrate geological heritage into broader conservation and management frameworks.

CONCEPTUAL FRAMEWORK

Geodiversity refers to the natural range—or diversity—of geological features (such as rocks, minerals, fossils, and structures), geomorphological elements (including landforms, topography, and physical processes), soils, and hydrology. It also includes their assemblages, structures, systems, and contributions to the landscape (Gray, 2013). Increasingly recognized as a fundamental component of nature, geodiversity complements biodiversity and plays a key role in ecological functioning, landscape evolution, and cultural identity (Gray, 2011; Gordon & Barron, 2013).

Geological heritage (hereafter referred to as geoheritage) comprises the most significant elements of geodiversity that enable the study, understanding, and interpretation of Earth's geological evolution. These elements hold exceptional scientific, educational, cultural, or touristic value, and therefore merit protection and sustainable use (*cf.* Carcavilla-Urquí *et al.*, 2007). These values are often embodied in geosites, or Places of Geological Interest (LIGs, by their acronym in Spanish), which are specific localities identified through a systematic inventory, supported by well-defined criteria and

robust scientific knowledge (García-Cortés *et al.*, 2014; Brilha, 2018).

Geoconservation encompasses a set of actions aimed at safeguarding geoh heritage through systematic processes such as inventories, value assessment, degradation risk analysis, and management planning (*cf.* Brilha, 2005). These strategies often adopt a transdisciplinary approach that integrates scientific and social dimensions. When effectively embedded in territorial planning, they can strengthen sustainable development, outreach, and education, particularly in regions where geological elements intersect with cultural values.

In this context, the geology of northwestern Mexico —long explored for its tectonic, volcanic, and mineral resources— offers a strong foundation for expanding geoh heritage inventories and advancing community-based conservation strategies. Coastal Sonora and the Midriff Islands stand out as a key area, where decades of geological and conservation work converge. However, growing land-use pressures demand new approaches for conservation and sustainable development, where geological knowledge may inform fresh insights and pathways toward integrated management.

For the inventory, this study adopts the term *LIG* and recommends reserving the term “geosite” for locations with active management strategies, UNESCO Global Geopark recognition, or other international designations, to avoid diminishing its significance. Furthermore, it does not adopt the definition of geosite proposed by Brilha (2016), which restricts the concept mainly to sites of scientific

value. Conducting a geoh heritage inventory inherently assume scientific relevance but may also include sites with educational, aesthetic, or cultural value important for integrated management and conservation.

STUDY AREA

Socio-environmental context

The study area lies within the Midriff Islands region of the Gulf of California (Bahre and Bourillón, 2002), encompassing the central coast of Sonora and the insular zone between Isla Tiburón —the largest island in Mexico— and the mainland. Isla Tiburón is separated from the mainland by the Canal del Infiernillo, a 40 km-long strait (Lancin, 1985). South of Isla Tiburón lie Isla Dátil and Isla Cholludo; while Isla San Esteban is in the central portion of this region.

On the mainland, desert coastal plains and bajadas border the Sierra Seri escarpment. Much of the area overlaps with the Comcaac (Seri) Indigenous territory, which includes Isla Tiburón and the Canal del Infiernillo. The Comcaac (~1,011 inhabitants) live in two communities within this territory: El Desemboque de los Seris in the north and Punta Chueca in the south (Figure 1a). Farther south lies Bahía de Kino (~8,000 inhabitants), whose economy is based on fishing and tourism (Instituto Nacional de Estadística y Geografía, 2020). Adjacent to this town is Laguna La Cruz, an important coastal lagoon that supports aquaculture and small-scale fisheries.

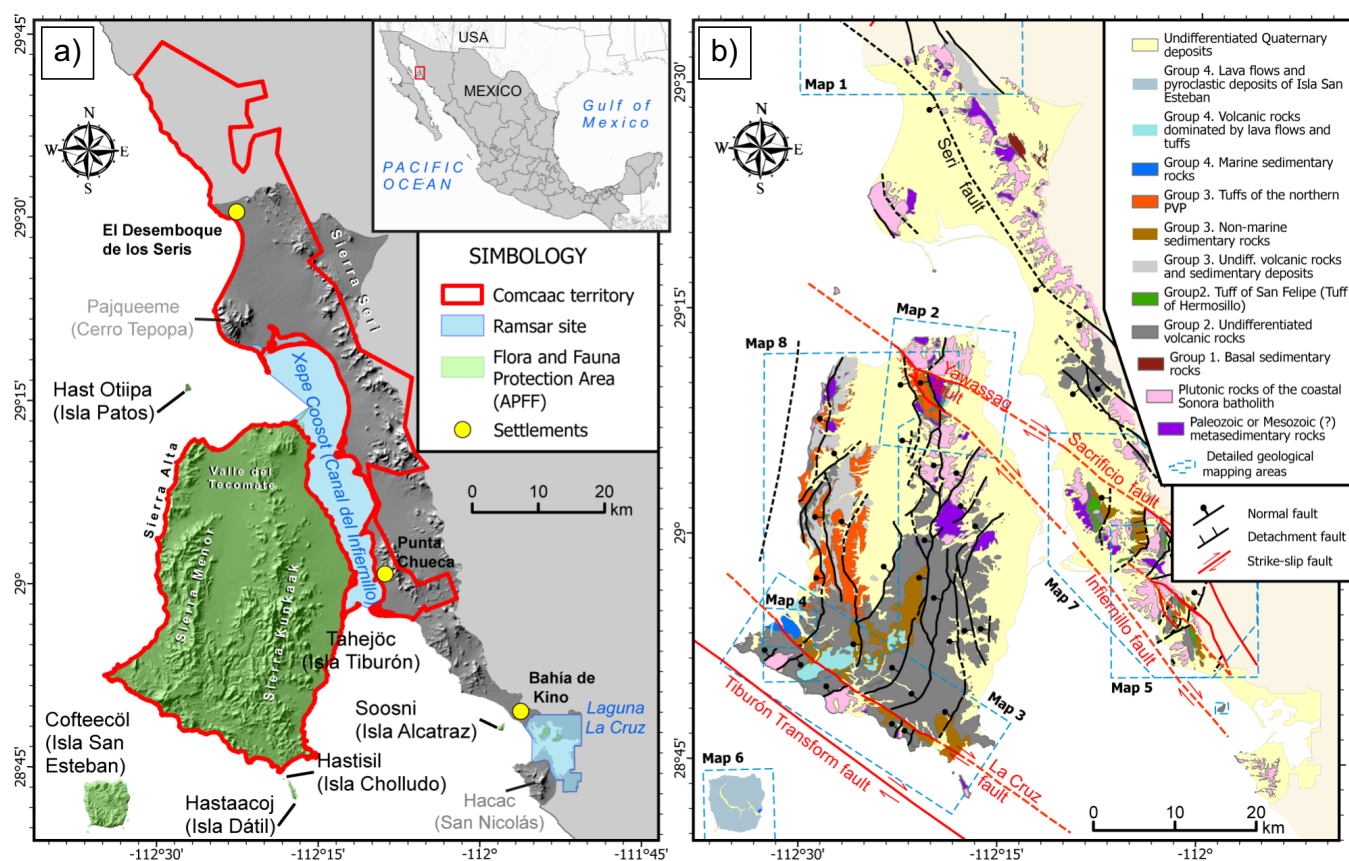


Figure 1. (a) The study area, shown with shaded relief (2,248.2 km²) qualifies as a limited area under Brilha (2016). (b) simplified geological map based on Gastil and Krummenacher (1976); Oskin and Stock (2003a), and Bennett *et al.* (2017). For detailed geology, refer to specific mapping sources (dotted polygons): Map 1 – Darin and Dorsey (2014) and Darin *et al.* (2016), Map 2 – Bennett *et al.* (2017), Map 3 – Bennett *et al.* (2016), Map 4 – Bennett *et al.* (2015), Map 5 – Bennett (2009) and Bennett *et al.* (2013), Map 6 – Calmus *et al.* (2008), and Map 7 and 8 – Oskin (2002) (Plate I and II). Names of localities are shown in Seri (*Cmiique iitom*), with Spanish names in parentheses.

The region holds national and international conservation designations. Since 1978, the islands and adjacent marine zones have been part of the Gulf of California Islands Flora and Fauna Protection Area (APFF-IGC; Diario Oficial de la Federación, 2001), managed by National Commission of Natural Protected Areas (CONANP, by its acronym in Spanish). Canal Infiernillo and Laguna La Cruz have also been designated as Ramsar sites due to their ecological value (Ramsar Sites Information Service, 2009, 2013). The area is listed as a UNESCO World Heritage Site list (United Nations Educational, Scientific and Cultural Organization [UNESCO], 2005), and was previously designated as a Man and Biosphere Reserve, a status that was withdrawn in 2020 (UNESCO, 2021). It is currently on the List of World Heritage in Danger (UNESCO, 2019), reflecting persistent ecological and governance concerns.

For over three decades, top-down conservation by government agencies and bottom-up initiatives by nonprofit organizations have promoted protection and education (e.g., Prescott College Kino Bay Center [PCKBC], 2024). However, geodiversity remains absent from planning and outreach. In light of tourism, urban growth, and aquaculture pressures, integrating geodiversity and geoheritage into conservation frameworks is now essential for effective, integrated territorial management.

Local geological framework

Although previous studies have addressed the regional geodiversity (Calmus *et al.*, 2008, 2017; Miros-Gómez *et al.*, 2024), this section focuses on lithological and structural features whose preservation is essential for understanding the geological evolution of the area, forming the basis for the geoheritage assessment.

Cenozoic lithostratigraphy is classified according to the region's most significant geological event: the opening of the Gulf of California. Accordingly, rocks are classified as pre-rift (>12 Ma) and syn-rift (<12 Ma) and further subdivided into four groups that overlie the local pre-Cenozoic substrate, following the regional framework proposed by Oskin and Stock (2003a).

Pre-Cenozoic basement comprises Paleozoic, Jurassic(?), and Late Cretaceous units (Oskin and Stock, 2003a; Ramos-Velázquez *et al.*, 2008). Paleozoic rocks are part of accreted terranes formed during the tectonic collision of Laurentia and Gondwana, correlated with the assembly of Pangea (Poole *et al.*, 2005). These rocks include highly deformed deep-marine sedimentary sequences, with westernmost facies described on Isla Dátil, where carbonized graptolites of late Middle to early Late Ordovician age have been reported (Poole *et al.*, 1993).

Paleozoic and Jurassic(?) rocks were later intruded and metamorphosed by Late Cretaceous igneous rocks (Ramos-Velázquez *et al.*, 2008), leading to uplift and erosion that left isolated metasedimentary remnants preserved as roof pendants. The plutonic rocks belong to the Cretaceous–Eocene Mexican Magmatic Arc, formed during subduction of the paleo-Farallon plate beneath the North America plate (Valencia-Moreno *et al.*, 2021). Locally, these plutons make up the coastal Sonora batholith, which defines two mountain belts: (1) an eastern belt along coastal Sonora, and (2) a western belt composed of several plutons from southern Isla Tiburón to Cerro Tepopa (Ramos-Velázquez *et al.*, 2008).

The Cenozoic sedimentary and volcanic stratigraphy is subdivided into four groups. Group I includes Oligocene–Miocene sedimentary rocks that unconformably overlie the basement (Oskin, 2002; Oskin & Stock, 2003a). These deposits are scarcely exposed in the study area, with occurrences limited to outcrops northwest of Isla Tiburón (Oskin, 2002) and north of Bahía de Kino (Bennett, 2009). Gastil *et al.* (1973) also mapped distinctive fluvial conglomerates

northeast of Sierra Seri, containing exotic Permian fusulinid-bearing limestone clasts.

Group II includes Early–Middle Miocene arc volcanic rocks, associated with the final subduction of the paleo-Farallon plate and coeval with Basin and Range extension. Outcrops consist of predominantly andesitic lava flows and volcanoclastic deposits, distributed across five structural domains separated and juxtaposed by rift-related faulting that postdates their deposition (Oskin & Stock, 2003a). In Isla Tiburón the Miocene volcanic rocks include andesitic and basaltic lava flows, especially in the south and central Sierra Menor and Sierra Kunkaak (see Oskin & Stock, 2003a; Bennett *et al.*, 2016), although the latter remains poorly mapped (Figure 1b).

The tuff of San Felipe, a welded rhyolitic ignimbrite dated at ~12.5 Ma, caps Group II deposits. It has been correlated across both margins of the Gulf based on lithology, geochemistry, and paleomagnetism (Stock *et al.*, 1999; Oskin, 2002). Its well-constrained age and widespread distribution make it a key structural–stratigraphic marker for reconstructing evolution of the Pacific–North America plate boundary after its emplacement (Stock *et al.*, 1999). This ignimbrite is well exposed in coastal Sonora, forming prominent faulted and tilted landforms in Bahía de Kino, as well as thick deposits near Punta Chueca, where previous studies suggest a probable vent slightly to the east (Oskin, 2002; Bennett *et al.*, 2013). On Isla Tiburón, discontinuous outcrops are exposed in the southern, western, and northern sectors, filling west-trending paleocanyons (Oskin & Stock, 2003b).

The following groups, III and IV, reflect the evolution of the Gulf of California oblique rift, initiated after the Middle Miocene (proto-Gulf stage), which brought major changes in volcanic and sedimentary deposition across northeastern Baja California and western Sonora (Oskin & Stock, 2003a). Group III comprises early syn-rift sequences (~12–6 Ma). Non-marine sedimentary rocks record the formation of rift-related basins, which were filled with fluvial deposits and later uplifted and exposed along the basin margins. The main rift basins are the Valle de Tecamate and the Canal del Infiernillo (Oskin, 2002).

Rift-related bimodal volcanism produced basaltic, andesitic, and rhyolitic lava flows and breccias that overlie the tuff of San Felipe, particularly in the western sector of Isla Tiburón and near Bahía de Kino (Oskin & Stock, 2003a; Bennett, 2009; Bennett *et al.*, 2013). The upper volcanic units of Group III, also predominantly exposed in the western sector of Isla Tiburón (Figure 1b), consist of ignimbrites dated to ~6.4–6.1 Ma, correlated with the northern Puertecitos Volcanic Province (PVP) (see Nagy *et al.*, 1999). These ignimbrites serve as robust key structural–stratigraphic markers to constrain the timing of rift localization and the magnitude of displacement along the northern Gulf (Oskin & Stock, 2003a, 2003b).

Group IV continues the syn-rift record of Group III, with the addition of marine strata and localized volcanism in southern Isla Tiburón (Oskin & Stock, 2003a). Particularly important are the fossiliferous marine sediments and volcanic deposits of the Southwest Isla Tiburón (SWIT) marine basin, a paleo-embayment formed by dextral displacement along the La Cruz fault (Gastil *et al.*, 1999; Bennett *et al.*, 2015). These deposits record the first marine incursion in the northern Gulf (~6.2 Ma), providing critical evidence for the tectonic transition and associated paleoenvironments. Volcanic rocks of the SWIT marine basin also help constrain the timing of marine sedimentation and fault activity (Bennett *et al.*, 2015).

A complementary case is Isla San Esteban, where volcanic and sedimentary units record tectono-volcanic processes active between 4.5 and 2.5 Ma, during the development of the Delfin basin. Volcanism is represented by basaltic andesites, dacites, and rhyolites, including adakitic lavas, likely derived from partial melting of a metasomatized subcontinental mantle. These rocks were emplaced in a setting of

already-thinned continental crust under an extensional regime (Calmus *et al.*, 2008).

A southeastern outcrop of fossiliferous shallow-marine sediments, overlain by pyroclastic flows, confirms a marine incursion during Pliocene, and correlates with SWIT marine basin deposits, supporting interpretations of crustal thinning and marine flooding during the late Miocene to early Pliocene in the northern Gulf of California (Desonie, 1992; Calmus *et al.*, 2008).

METHODS

The assessment of LIGs followed an adapted methodology based on the *Inventario Español de Lugares de Interés Geológico* (IELIG, García-Cortés *et al.*, 2014), the guidelines proposed by the *Asociación de Servicios de Geología y Minería de Iberoamérica* (ASGMI, 2018), and the approach developed by Brilha (2016). The adapted methodology was further refined to better align with the regional context (Figure 2). The detailed list of criteria and adaptations to indicators and parameters is available in the Supplementary Material (Tables S1–S8).

The inventory of LIGs was consolidated upon completion of the qualitative evaluation phase. Quantitative assessment is a useful tool to reduce subjectivity and enable objective comparison among sites within the same context. It is particularly effective for classifying sites according to their value or potential, as well as their risk of degradation. Its main purpose is to support strategic decision-making

for LIG conservation, rather than to establish a fixed or absolute measure of their value.

Data collection and site selection

Site identification began with a bibliographic review to define the main geological frameworks of the study area and to compile a preliminary list of LIGs. This facilitated expert input and ensured alignment between site features and regional geology.

An expert consultation was conducted by adapting the form from García-Cortés *et al.* (2014), applying a qualitative and exploratory approach due to project constraints and limited specialist availability. Five geologists proposed sites using standardized criteria, complemented by follow-up questionnaires or participation in fieldwork. Additional input from ecology and cultural heritage specialists helped identify interdisciplinary values. Field validation was conducted between 2022 and 2024. Members of the Comcaac community participated in the visits, providing crucial cultural knowledge and perspectives.

Geological interest and relevance level

Each LIG was classified according to one or more types of geological interest, with at least one designated as the primary justification for its inclusion in the inventory. The full list of interests is provided in the Supplementary Material.

Sites were also assigned to a relevance level—local/regional, national, or international—based on expert input, literature review, and attributes such as representativeness, rarity, and overall quality.

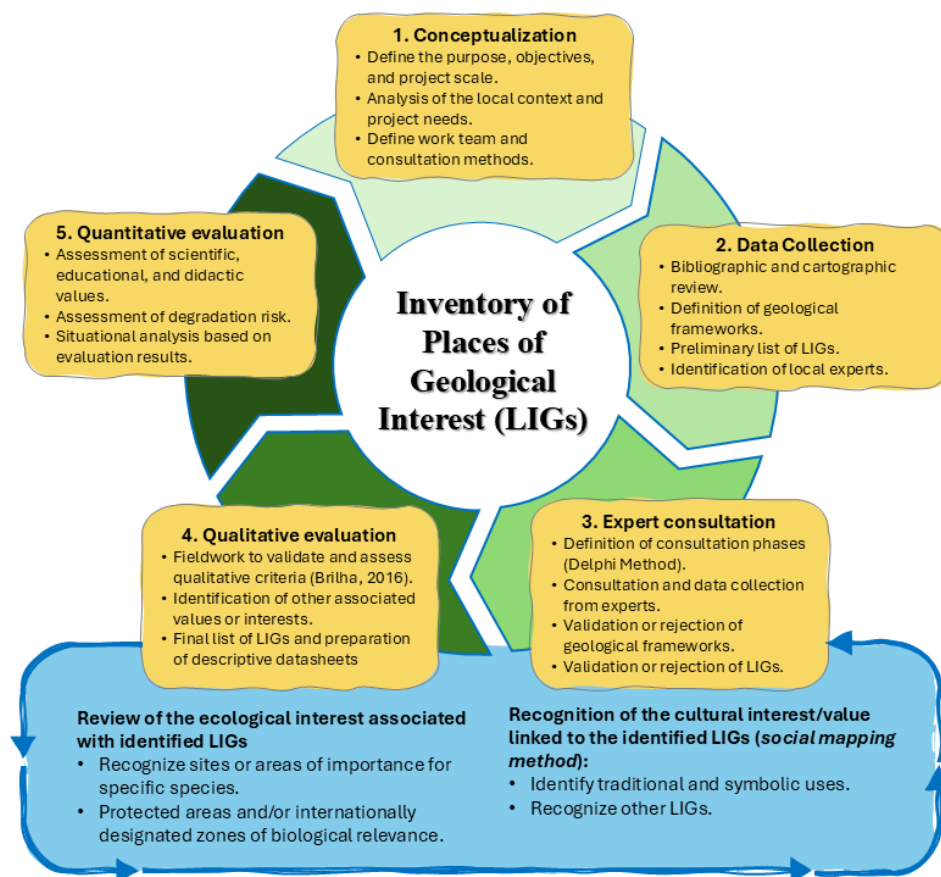


Figure 2. Methodological framework developed in this study. The process in the blue box corresponds to the identification of sites with cultural value. This social methodology was carried out in parallel to the geoheritage inventory and forms part of a complementary study currently in progress.

This classification contextualizes each LIG broader significance. It is important to note that national and international relevance should be considered preliminary, pending the development of formal comparative inventories at broader (e.g., national) scales.

Valuation criteria and scoring

The quantitative assessment of LIGs was structured around three distinguishable value categories: scientific, educational, and touristic potential. According to García-Cortés *et al.* (2014), site evaluation should consider both intrinsic value and potential for use. Scientific value is primarily based on intrinsic characteristics, such as representativeness, rarity, and integrity, that make a site significant for advancing geological knowledge. In contrast, educational and touristic values relate to a site's actual or potential capacity to support learning and recreational activities, respectively.

Each category was evaluated independently using a weighted scoring system, in which specific indicators —associated with defined criteria— were assigned numerical scores ranging from 0 to 4. These indicators reflect measurable attributes of each site and serve as the operational basis for scoring. Each score was then weighted according to the relative importance of its corresponding criterion (see Supplementary Material), and final values were calculated as normalized weighted sums (Equation 1), yielding results from 0 to 10:

$$V = \frac{1}{40} \sum_{i=1}^N w_i x_i \quad (\text{Equation 1})$$

In which V is the final value (scientific, educational, or touristic), N is the number of criteria considered for that value category (see Table S1 in the Supplementary Material), w_i is the weight assigned to each criterion i (in %), and x_i is the score assigned to the criterion i (based on the indicators, with parameter ranging from 0 to 4). The division by 40 normalizes the results, yielding a final value between 0 and 10.

This scoring system allows for objective comparison among sites and facilitates their classification by using potential or for conservation. However, final prioritization also considered expert judgment and contextual factors such as existing threats, and associations with cultural or ecological values.

Degradation risk assessment

In addition to value-based prioritization, a degradation risk assessment was applied to all LIGs, following the method proposed by Brilha (2016). This assessment considered five weighted criteria (see Table S2 in the Supplementary Material), with values calculated using Equation 1. Scores <5 are classified as Low, those between 5.1 and 7.5 as Medium, and those >7.5 as High.

This analysis helped identify high-value sites that are also highly vulnerable, informing management priorities. It also revealed cases where weak legal protection or growing human pressure increase the urgency for conservation. Qualitative field observations were included to contextualize root threats and refine recommendations.

RESULTS

Qualitative assessment of the LIGs

A total of 24 LIGs were identified and classified into six geological frameworks, some with specific frameworks (Figure 3). This classification contextualizes each site by origin and relevance to the region's tectonic and volcanic evolution, underscoring the area's geodiversity. Three additional sites (yellow asterisks) were proposed for future inclusion, based on prior documentation and expert input. These sites were not visited due to access limitations but may be evaluated in future updates.

Table 1 summarizes the abiotic, biotic, and cultural interests of the LIGs. While primarily descriptive, this table also supports early-stage management by revealing compatibilities or conflicts between site interests. For example, a site with geomorphological interest and high touristic potential may not be suitable for recreational use if it overlaps with sensitive ecological features —such as nesting or feeding habitats— or with cultural areas whose intended uses are not aligned with tourism.

Most LIGs ($n=22$) exhibit geomorphological interest, which was the primary interest in 16 cases. Tectonic/structural and stratigraphic interests were also common ($n=8$ each). The prevalence of geomorphological features reflects the influence of coastal and tectonic processes in shaping landforms and exposing geological records. Although many LIGs are located near the coast, their boundaries often extend several kilometers inland. However, their visibility from the shoreline enhances their educational and touristic potential while minimizing direct human impact on the sites (Figure 4).

Cultural interest was identified in 18 sites, often linked to traditional uses such as resource gathering, traditional settlements or ceremonies (see Bowen, 2000; Luque & Robles, 2023). Biotic interest was identified at 16 sites, particularly those located in ecologically sensitive ecosystems such as coastal lagoons and small islands, many of which are also the focus of ongoing conservation or monitoring programs (Wilder *et al.*, 2008, 2025).

Quantitative assessment of LIGs

Results are presented using LIG codes (see Figure 3). Assessments were conducted independently for scientific value (Table 2), educational and touristic potential (Table 3), and risk of degradation (Table 4), with threats summarized in Table 5. Descriptions of the LIGs are condensed in Table S9 of the Supplementary Material.

Scientific value

Scientific value scores were mainly influenced by the 'use limitation' and 'rarity' criteria. Eight LIGs obtained scores >7, with five reaching the highest scores recorded ($V=8.3$). These correspond to well-studied sites that preserve key records of regional and international geological history. High-scoring examples include sites in the Coastal Sonora fault zone (VF-LIG4) and La Cruz fault area in southern Isla Tiburón (VF-LIG7, VF-LIG8), whose structural and stratigraphic records are essential for understanding the Gulf of California rifting (Figures 4a–4c; Bennett *et al.*, 2013, 2016).

Punta Reina cliffs (VF-LIG9; Figure 4f) stand out for preserving pyroclastic deposits correlated with the northern PVP, interpreted as conjugate margins exposures displaced by rifting (Oskin & Stock, 2003a, 2003b). The SWIT marine basin (CM-LIG10) scored high for preserving the only known fossiliferous Miocene marine deposits on the eastern margin of the northern Gulf, documenting a synchronous marine incursion in the region (Bennett *et al.*, 2015). Other LIGs with high scores (RP-LIG1, PC-LIG15, PG-LIG24) represent the most relevant examples of their type in the study area. Four sites (VP-LIG11, PC-LIG12–14) received intermediate scores, despite their scientific significance (Figure 4d and 4g).

Most high-scoring LIGs also have strong educational potential (Table 3). Many are already used for teaching by local institutions and remain well preserved due to their remoteness and protective conditions (e.g., APFF-IGC, Indigenous Territory).

Educational potential

Educational scores were generally higher than scientific or touristic values, influenced by criteria such as 'accessibility', 'use limitations', and 'safety', while 'geodiversity' significantly enhanced

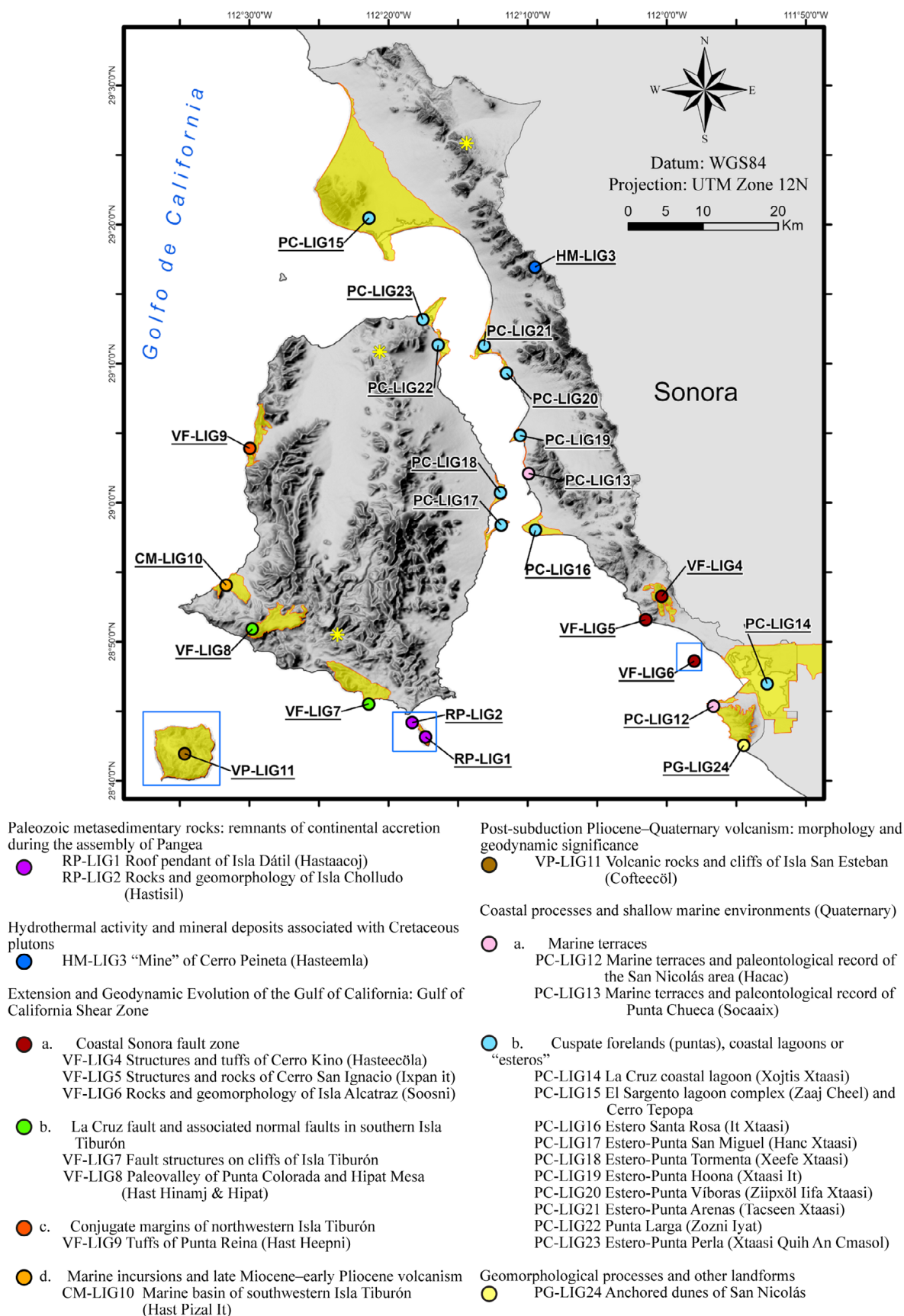


Figure 3. Geological frameworks and corresponding LIGs in the study area. Color codes help to identify the main geological frameworks and specific frameworks in which each LIG is located. Yellow asterisks indicate sites proposed for future assessments, and yellow-green shaded polygons represent the proposed area of each LIG.

educational value (Table 3). Thirteen LIGs ($V > 7.0$) combine geological significance with strong biological and cultural connections. These sites are frequently used for multidisciplinary research and university-level courses (VF-LIG4, VF-LIG5, VF-LIG6, PC-LIG14–17). Others are visited during geology or geomorphology courses (*e.g.*, VF-LIG7–8, PC-LIG12). Intermediate scores dominate among less frequently visited sites. Overall, results reflect regional geodiversity and the active role of academic and conservation institutions.

Touristic potential

Touristic value among the LIGs varied based on 'accessibility' and 'proximity' to existing tourist areas (Table 3). The highest-scoring sites form part of the region's main ecotourism attractions. Despite limited infrastructure, they are frequently visited due to their aesthetic value, largely shaped by geomorphology (VF-LIG4, VF-LIG6, PC-LIG14–16, and PG-LIG24). In some cases, geomorphological and ecological features overlap, enabling activities such as sport fishing, birdwatching, and kayaking (RP-LIG1, PC-LIG14, PC-LIG16).

Marine terraces (PC-LIG12–13; Figure 4g) scored highly due to their proximity to recreational or cultural areas, though their fragility

demands careful management. Intermediate scores were associated with remote or private sites that nonetheless hold geotourism potential (Figure 4a–4b; VF-LIG5, VF-LIG7). Other sites (*e.g.*, PC-LIG15, PC-LIG17) are already visited but require guided access due to remoteness and permit restrictions.

In summary, only two LIGs scored highly ($V > 7.0$) across all three categories (scientific, educational, and touristic), both characterized by distinctive geomorphological features (VF-LIG4 and PG-LIG24). Seven other LIGs scored highly in two categories, including insular sites (RP-LIG1, VF-LIG7–9) and those with marine terraces and coastal wetlands (PC-LIG13–15). These results underscore the regional importance of several LIGs; however, high scores do not imply suitability for intensive public use. It is therefore essential to consider these values alongside degradation risk and identified threats.

Degradation risk and associated threats

Five LIGs exhibit high degradation risk due to moderate-impact activities (Table 4 and 5). Notably, VF-LIG4 and PG-LIG24 also scored highly in all three value categories, reflecting both their use potential and vulnerability. Laguna La Cruz (PC-LIG14) showed the highest

Table 1. Main abiotic, cultural, and biotic interests identified for each LIG (most relevant in bold uppercase). Interests related to edaphology, collections, and mining were considered, though none were present. A possible edaphological dimension merits further study (see Wilder *et al.*, 2008; and references therein). Full list of interests in Supplementary Material.

LIG	Abiotic									Cultural			Biotic			
	Stratigraphic	Paleontological	Tectonic-Structural	Petrological	Sedimentological	Mineralogical	Geomorphological	Hydrogeological	Geological history	Historical	Archaeological	Geosymbol	Endemism	Feeding site	Nesting and breeding site	Protected and migratory species
RP-LIG1	X	x	x				x		x				x	x	x	x
RP-LIG2							X						x	x	x	x
HM-LIG3						X						X				
VF-LIG4			X	X			x		x		x	X				
VF-LIG5			x				X					X				
VF-LIG6							X					X		x	x	x
VF-LIG7	x		X	x			x		x					x		
VF-LIG8	x		X				x		x			X				
VF-LIG9	x		X	X			x		x							
CM-LIG10	X	X	X	x	x				x		x					
VP-LIG11		x	x	X			X		x	x	x	X	x	x	x	x
PC-LIG12	X	X			x		x									
PC-LIG13	X	X			x		x									
PC-LIG14					x		X	x		x	x	X		x	x	x
PC-LIG15	x	x					X	x	x	x	x	X		x	x	x
PC-LIG16							X	x				X		x	x	x
PC-LIG17							X	x				X		x	x	x
PC-LIG18							X	x				X		x	x	x
PC-LIG19							X	x				X		x	x	x
PC-LIG20							X	x				X		x	x	x
PC-LIG21							X	x				X		x	x	x
PC-LIG22							X	x				X		x	x	x
PC-LIG23							X	x				X		x	x	x
PG-LIG24					x		X					X		x		

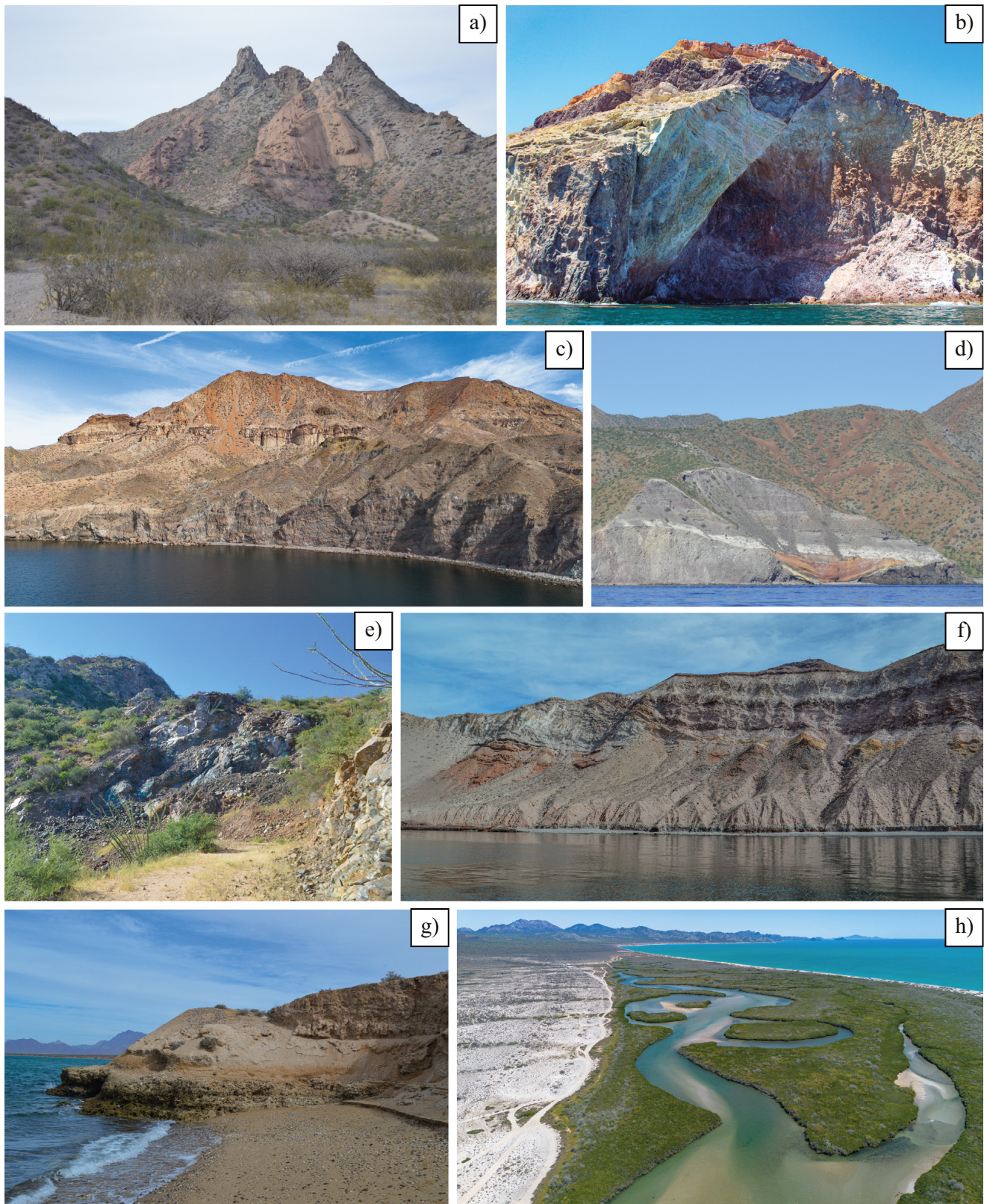


Figure 4. (a) VF-LIG4 – Cerro Kino (*Hasteecöla*), showing prominent peaks formed by the tuff of San Felipe deposits, which are strongly tilted. (b) VF-LIG7 – normal fault exposed in cliffs at *Hehe Hasoaj Quih An Ihiip* “*Iyat*”. (c) VF-LIG8 – Northwest view of the Miocene paleovalley underlying the *Hast Hinamj* (Punta Colorado) volcano. (d) VP-LIG11 – Coastal cliffs of Isla San Esteban, showing a paleochannel filled by brown andesitic tuff, overlain by white ash tuff (Calmus *et al.*, 2008). HM-LIG3 – The “mine” at Cerro Peineta (*Hasteemla*) is a skarn-type deposit, geologically unique within the study area. (f) VF-LIG9 – Marine cliff at Punta Reina showing important pyroclastic units, including the tuff of San Felipe (~12.6 Ma), unconformably overlain by the tuff of Mesa Cuadrada (~6.3 Ma) (Oskin and Stock, 2003b). (g) PC-LIG13 – Marine terraces and fossil record at Punta Chueca (*Socaaix*). (h) PC-LIG16 – Estero Santa Rosa (*It Xtaasi*) coastal lagoon.

Table 2. Scientific value (ScV) of each LIG. Scores >7.0 are in bold. Includes relevance level for each site. **Note:** Criteria abbreviations (R, L, K, C, Ga, Ra, U) are explained in Tables S1 and S2 of the Supplementary Material.

Code	R	L	K	C	Ga	Ra	U	ScV	Relevance
RP-LIG1	4	2	1	4	4	2	1	7.1	National
RP-LIG2	1	0	1	4	1	1	1	3.1	National
HM-LIG3	2	0	1	2	2	2	1	3.6	Local/Regional
VF-LIG4	4	2	4	4	4	4	1	8.3	International
VF-LIG5	1	0	1	2	1	2	1	2.8	Local/Regional
VF-LIG6	1	0	1	4	1	2	1	3.5	Local/Regional
VF-LIG7	4	2	4	4	4	4	1	8.3	International
VF-LIG8	4	2	4	4	4	4	1	8.3	International
VF-LIG9	4	2	4	4	4	4	1	8.3	International
CM-LIG10	4	2	4	4	4	4	1	8.3	International
VP-LIG11	2	1	4	4	4	4	1	6.3	National
PC-LIG12	2	2	4	4	4	1	1	5.6	National
PC-LIG13	2	2	4	4	4	1	2	5.9	National
PC-LIG14	2	1	4	4	2	2	2	5.5	National
PC-LIG15	4	1	4	4	4	4	2	8.0	National
PC-LIG16	2	1	2	4	2	1	2	4.9	National
PC-LIG17	2	0	2	4	2	1	1	4.1	National
PC-LIG18	2	1	2	4	2	1	1	4.6	Local/Regional
PC-LIG19	1	0	2	4	2	1	2	3.6	Local/Regional
PC-LIG20	2	0	2	4	2	1	2	4.4	Local/Regional
PC-LIG21	2	0	2	4	2	2	2	4.8	Local/Regional
PC-LIG22	1	0	1	4	2	2	2	3.9	Local/Regional
PC-LIG23	2	0	2	4	2	2	2	4.8	National
PG-LIG24	4	1	2	4	1	4	2	7.4	National

risk ($V=8.8$), due to intensive touristic and aquaculture activity (Table 4). Similarly, San Ignacio (VF-LIG5) showed a high score ($V=8.4$), associated with ongoing touristic development.

Although these LIGs might be considered priorities for conservation actions, degradation risk assessment alone has a critical limitation: it does not provide enough information for understanding the root causes of threats, as it relies on general criteria that require further examination. To address this, specific threats were identified and described (Table 5), providing a foundation for developing an integrated situation analysis.

A critical understanding of the socio-environmental context is also essential. As previously noted, some sites lie within Indigenous territories or in areas with national or international designations, which may influence the feasibility management actions (Table 4). In this regard, engaging local communities and reviewing existing management and land-use plans are key to developing viable conservation strategies.

Seven additional LIGs showed moderate degradation risk, also requiring attention. Cross-referencing risk levels with specific threats helps refine priorities and guide context-sensitive conservation actions.

DISCUSSION

Criticisms about assessment methodologies

In Mexico, the use of quantitative evaluation methods for LIGs (or geosites) has increased in recent years, but this growing use has also generated debates among specialists regarding their objectivity, comparability, and actual utility for conservation.

Frequent criticism concerns the flexibility of indicators related to criteria, which—if poorly designed—may introduce bias or subjectivity into the assessment. While this is a valid concern, it often overlooks that structured indicators aim to reduce subjectivity by defining measurable attributes grounded in local and technical context. Their use is standard practice in ecosystem management, where they are essential for tracking conservation progress, monitoring effectiveness, and guiding recovery efforts (Conservation Measures Partnership [CMP], 2020).

Another concern is the subjectivity of expert judgment in scoring certain criteria, which may vary depending on the evaluator's background or familiarity with the area. However, this does not necessarily compromise the validity of the results. When guided appropriately and supported with scientific literature and geospatial data, expert input plays an important role. Ultimately, the quality and depth of the project team's knowledge of the area are crucial, and inventories should be considered provisional and subject to future updates.

These assessment methods should not be used to "prove" heritage status. Doing so oversimplifies the complex cultural, scientific, and political processes involved in heritage recognition (*i.e.*, patrimonialization). Instead, they should serve as tools for identifying priorities and supporting strategic planning. Their use must be thoughtful and adapted to each context in order to support realistic geoconservation strategies.

Situation analysis based on assessment results

Quantitative methodologies such as the one proposed by Brilha (2016) offer a useful framework for organizing LIGs data. Figure 5 provides a visual summary that facilitates comparative analysis by highlighting the dominant value per site, as well as its apparent conservation priority when these values are contrasted with degradation risk. However, this prioritization logic, often based on simply adding value scores (scientific, educational, or touristic) to degradation risk, should be approached with caution, as it can obscure key aspects of site management. Ranking approaches alone may lead to actions driven by perceived urgency rather than strategic opportunity.

Moreover, this additive model could oversimplify specific threats, existing legal protections and governance conditions (*e.g.*, protected areas, Ramsar sites, Indigenous territories) that affect the feasibility of protection and use. Therefore, a robust situation analysis should include not only quantitative assessments and the scrutiny of threat types and causes, but also stakeholder mapping and relevant policy instruments such as management plans and land-use planning programs. These elements are essential for moving from assessment to a realistic, context-sensitive geoconservation strategy.

Barriers to scientific recognition

None of the LIGs reached the maximum possible scientific score ($V=10$; Figure 5), mainly due to two key limitations. First, many sites are located in remote areas within the APFF-IGC, where restricted access, natural obstacles, and the need for permits and specialized logistics hinder scientific research and limit their perceived relevance. Secondly, although some LIGs may meet the characteristics of international type localities, Mexico lacks systematic efforts to obtain such designations. This absence may bias evaluations by underrepresenting the global relevance of certain sites.

Although many LIGs are in remote areas within the APFF-IGC, this isolation has contributed to their good state of conservation. Nonetheless, their preservation alone should not justify a lack of recognition. These sites merit visibility and protection based on their intrinsic geological significance. In fact, several of them, despite being remote, are already visited by international researchers and students

Table 3. Educational (EdV) and touristic (TsV) potential of each LIG. Scores >7.0 are in bold. Note: Criteria abbreviations (Vu, Ac, U...) are explained in Table S1 of the Supplementary Material.

Code	Vu	Ac	U	Sf	Li	Pd	Hr	B	Re	O	Dp	Ga	Ip	Se	Zr	EdV	TsV
RP-LIG1	4	1	2	2	3	1	3	3	3	4	2	4	4	3	3	6.6	7.0
RP-LIG2	4	1	2	2	3	1	3	1	3	4	3	2	4	3	3	6.4	6.3
HM-LIG3	2	1	2	1	2	1	4	1	2	3	1	3	2	3	2	4.5	4.5
VF-LIG4	2	4	1	3	4	3	4	1	3	3	4	4	4	3	4	8.0	7.1
VF-LIG5	2	4	1	4	4	3	4	1	1	3	3	2	4	3	4	7.0	6.9
VF-LIG6	3	1	1	4	4	3	4	2	2	4	4	2	4	3	4	7.5	7.1
VF-LIG7	4	1	1	2	3	1	4	0	4	4	4	4	4	3	3	7.4	6.1
VF-LIG8	4	1	1	1	2	1	4	0	4	4	4	4	4	3	1	7.0	5.5
VF-LIG9	4	1	1	1	2	1	4	0	4	4	4	4	4	3	1	7.0	5.5
CM-LIG10	3	1	1	1	2	1	4	0	4	4	1	4	3	3	4	5.3	5.4
VP-LIG11	4	1	1	1	2	1	4	0	2	4	4	4	4	3	1	6.8	5.0
PC-LIG12	3	3	1	3	3	3	4	3	2	4	4	4	4	3	4	8.3	7.6
PC-LIG13	3	4	3	3	3	3	4	1	2	4	4	3	4	3	4	8.3	7.4
PC-LIG14	2	4	4	4	4	3	4	2	2	3	4	3	4	3	4	8.4	7.9
PC-LIG15	3	2	2	1	1	2	4	2	3	4	4	4	4	3	4	7.3	6.5
PC-LIG16	3	3	2	2	4	3	4	2	2	4	4	3	4	3	4	7.9	7.3
PC-LIG17	3	1	2	3	3	2	4	3	2	4	4	3	4	3	4	7.5	7.1
PC-LIG18	2	1	1	2	3	2	4	1	2	3	4	3	4	3	3	6.4	5.5
PC-LIG19	3	2	2	2	3	2	4	0	2	3	4	3	4	3	1	6.9	5.5
PC-LIG20	3	2	2	2	3	2	4	0	2	3	4	3	4	3	1	6.9	5.5
PC-LIG21	3	2	2	2	3	2	4	0	2	3	4	3	4	3	1	6.9	5.5
PC-LIG22	4	1	1	2	3	2	4	0	2	3	4	2	4	3	1	6.5	5.4
PC-LIG23	4	1	1	2	3	2	4	0	2	3	4	3	4	3	2	6.8	5.5
PG-LIG24	2	2	4	3	3	3	4	3	3	4	4	3	4	3	4	8.0	7.8

Table 4. Degradation risk (DrV) of each LIG. Highest scores in bold. Protection/designation statuses: APFF-IGC (Flora and Fauna Protection Area of the Gulf of California Islands), UMA (Environmental Management Unit), Ramsar (Wetland of International Importance), TI (Comcaac Territory), ECZ (Environmental Conservation Zone). **Notes:** (1) LIGs marked with an asterisk (*) correspond to Group 1, as discussed in the text; (2) Criteria abbreviations (A, B, C...) are explained in Table S2 of the Supplementary Material.

Code	A	B	C	D	E	Weighted score	DrV	Protection status
RP-LIG1	0	0	2	1	1	1.6	Low	APFF-IGC
RP-LIG2	0	0	2	1	1	1.6	Low	APFF-IGC
HM-LIG3	3	0	1	2	1	4.1	Low	TI
VF-LIG4*	3	4	3	4	3	8.4	High	ECZ
VF-LIG5*	3	4	3	4	3	8.4	High	ECZ
VF-LIG6	1	1	1	1	3	3.0	Low	APFF-IGC
VF-LIG7	0	1	2	1	1	2.1	Low	APFF-IGC; TI
VF-LIG8	0	0	2	1	1	1.6	Low	APFF-IGC; TI
VF-LIG9	0	0	2	1	1	1.6	Low	APFF-IGC; TI
CM-LIG10	3	1	2	1	1	4.8	Low	APFF-IGC; TI
VP-LIG11	1	0	2	1	1	2.5	Low	APFF-IGC
PC-LIG12*	4	1	1	2	3	6.0	Medium	UMA (Partial)
PC-LIG13*	4	2	4	2	2	7.8	High	TI
PC-LIG14*	4	4	2	4	3	8.8	High	Ramsar; APFF-IGC (partial)
PC-LIG15	2	4	4	2	2	7.0	Medium	TI; Ramsar
PC-LIG16	2	2	2	3	3	5.6	Medium	TI; Ramsar
PC-LIG17	1	1	1	1	2	2.8	Low	APFF-IGC; Ramsar; TI
PC-LIG18	3	4	1	1	2	6.0	Medium	APFF-IGC; Ramsar; TI
PC-LIG19	2	3	4	2	2	6.5	Medium	Ramsar; TI
PC-LIG20	1	3	4	2	2	5.6	Medium	Ramsar; TI
PC-LIG21	1	2	4	2	2	5.1	Medium	Ramsar; TI
PC-LIG22	0	0	2	1	2	1.9	Low	APFF-IGC; Ramsar; TI
PC-LIG23	3	1	2	1	2	5.0	Low	APFF-IGC; Ramsar; TI
PG-LIG24*	4	4	3	2	3	8.5	High	UMA, ECZ (Patial)

Table 5. Main threats and affected LIGs. Contributing factors are based on field evidence. Not all activities occur at every site, but each LIG is impacted by at least one threat. Sites with high degradation scores are in bold.

Threats	Threatened LIGs	Contributing factors
Tourism-related disturbances	VF-LIG6; PC-LIG13 ; PC-LIG14 ; PC-LIG15; PC-LIG16; PG-LIG24 .	• Off-road racing and dune driving (erosion). • Creation of trails and informal paths. • Unregulated camping. • General solid waste or illegal dumping (e.g., construction debris, tires).
Fishing and aquaculture-related disturbances	VF-LIG7; CM-LIG10; PC-LIG11; PC-LIG14 ; PC-LIG16; PC-LIG18; PC-LIG19; PC-LIG20; PC-LIG21.	• Establishment of fishing camps and dumping of solid and hazardous waste (e.g., oil, fuel). • Aquaculture infrastructure causing deterioration of geomorphological features. • Aquaculture-related changes in sedimentation and erosion patterns.
Infrastructure development (housing/tourism)	VF-LIG4 ; VF-LIG5 ; PC-LIG14 .	• Land subdivision and real estate development (privatization). • Construction of hotels and tourist facilities.
Climate change and sea-level rise	VF-LIG7; CM-LIG10; PC-LIG12; PC-LIG13 ; PC-LIG14; PC-LIG14 ; PG-LIG24 .	• Coastal and fluvial erosion and flooding. • Rockfalls.
Other	VF-LIG4 ; PC-LIG14 ; PC-LIG16.	• Vandalism (e.g., graffiti).

(e.g., Price *et al.*, 2019), further reinforcing the need to promote their study, appreciation, and inclusion in broader conservation strategies.

Educational and outreach potential

As previously noted, the LIGs in the study area obtained higher scores for educational value. The high values observed are largely driven by the diversity of geological features they exhibit. Many sites include elements suitable for university-level teaching, while their biological and cultural associations broaden the potential for engaging diverse audiences. The region also benefits from ongoing non-formal education initiatives —led by academic institutions and nonprofit organizations— that integrate geology into broader conservation, ecology, and marine science topics (PCKBC, 2024). This highlights the interdisciplinary nature and visual appeal of the local geological landscapes.

These conditions provide a solid foundation for outreach and education programs centered on geoheritage, including guided visits, interpretive materials, and cross-cutting educational content. Importantly, any such strategy must be tailored on a case-by-case basis, particularly in sites with a high risk of degradation (e.g., marine terraces), to avoid intensifying existing pressures. Furthermore, implementation should follow existing regulations (e.g., CONANP permits) and actively involve the Comcaac community to ensure culturally appropriate and sustainable outcomes.

Prospects for geotourism development

Most high-scoring LIGs are located in or near popular recreational areas, which attract frequent visitors due to their easy access and aesthetic value. Despite this potential, responsible or sustainable tourism in the study area remains limited. Sun-and-beach tourism continues to dominate and is the main economic activity after fishing (Chavez Valdez *et al.*, 2022). The lack of diverse recreational offerings places increasing pressure on coastal ecosystems and concentrates tourism demand in high season (spring and summer).

The results of this study highlight the geological significance of several sites that have not been fully integrated into tourism development. Several LIGs identified in this study offer untapped opportunities for responsible tourism, as geotourism that also incorporate cultural and biological values. Well-designed itineraries could help diversify local economies, alleviate environmental stress on overused areas, and foster public appreciation of geoheritage, especially during off-peak

periods. However, their implementation requires careful planning and meaningful engagement with local communities and landowners to ensure long-term sustainability.

Alternatives for the management of geoheritage in the study area

Mexico lacks a specific legal framework for the inventory, assessment, and conservation of geoheritage. Consequently, the management of LIGs depends on indirect mechanisms such as existing environmental policies, land-use planning tools, and collaborative efforts by CONANP, academic institutions, nonprofit organizations, and local communities. This section outlines management alternatives for the LIGs based on current institutional and territorial arrangements.

Within the study area, 13 LIGs are located within the federal APFF-IGC (see Table 4). Nine overlap with Ramsar sites and Comcaac territory, while two lie entirely within Comcaac territory without formal protection. Four LIGs, one within an Environmental Management Unit (UMA, by its acronym in Spanish) and three in Bahía de Kino, are situated on private and public lands designated as Environmental Conservation Zones (ECZs) under the Municipal Urban Development Program of Hermosillo (PMDUH, by its acronym in Spanish; Instituto Municipal de Planeación de Hermosillo, 2023).

Based on this territorial and legal context, two main groups of LIGs can be identified according to their management conditions: (1) sites with limited or no formal protection, including those within ECZs, which face a high risk of degradation, lack active stewardship, and are particularly vulnerable due to their proximity to expanding urban areas; and (2) sites under broader, often indirect protection frameworks, such as those within the APFF-IGC, Ramsar sites inside the Comcaac territory, which have some degree of social or institutional stewardship and generally located in more remote areas.

The conditions of the LIGs in the first group (marked in Table 4) call for their prioritization in conservation planning. To address these, the following actions are proposed:

- Legal integration: Incorporate LIGs into updates to municipal and population center development plans to enable their formal recognition and protection.
- Stakeholder engagement: Raise awareness among landowners and local authorities to encourage risk mitigation and conservation of LIGs.
- Sustainable use: Promote low-impact, community-led geotourism as a strategy for site protection and local benefit.

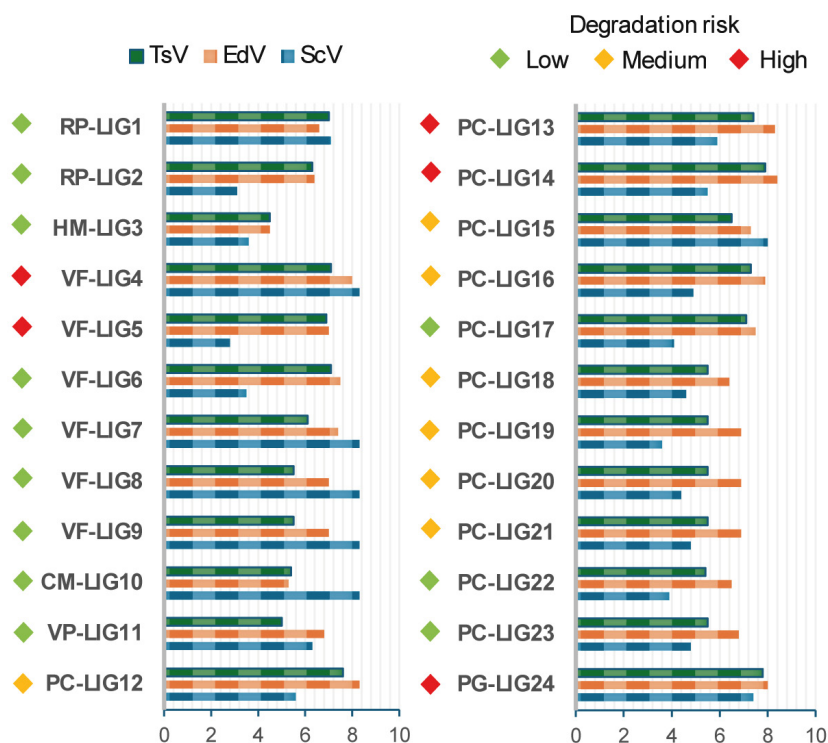


Figure 5. Grouped bar chart of scientific (ScV), educational (EdV), and touristic (TsV) values for each LIG. The chart highlights the dominant value, indicating each site's primary significance for geoconservation and outreach strategies.

Land-use and urban development programs can play an important role in advancing these actions. The current PMDUH includes provisions for the creation of local protected areas (e.g., Laguna La Cruz), as well as the development of green infrastructure and sustainable tourism activities that align with the values and potential uses identified for the LIGs. However, integrating these sites into such programs will also require updates to local environmental regulations to ensure proper implementation and effectiveness.

For the second group, actions aim to enhance the recognition and management of LIGs:

- Integration into management instruments: Incorporate LIGs as formal conservation targets within management plans of natural protected areas and Ramsar sites.
- Capacity-building and coordination: Strengthen the technical capacities of local managers, conservation groups, and partner organizations to support the inclusion of LIGs in ongoing conservation efforts.
- Geoeducation and local engagement: Promote awareness and informed decision-making through educational initiatives and community participation.
- Sustainable use strategies: Develop locally appropriate approaches for the sustainable use of LIGs, focusing on low-impact activities that support local economic diversification.

Management programs represent a valuable mechanism for LIG protection. These instruments are typically organized around defined "conservation targets," which guide protection objectives, actions, and monitoring (CMP, 2020). Although such targets have traditionally focused on biodiversity, there is a clear opportunity to include LIGs as formal conservation targets, allowing for the design of tailored strategies for their protection and monitoring. Likewise, Ramsar site management instruments—despite being non-statutory—

can incorporate geoconservation components when developed collaboratively with communities and local authorities.

As part of these management alternatives, it is also important to recognize that geoheritage often overlaps with cultural heritage, especially in Indigenous contexts where the territory holds both tangible and intangible significance. Some authors explore integrated approaches that enable a more holistic understanding (Reynard & Giusti, 2018; Pijet-Migoñ & Migoñ, 2022). In practice, acknowledging this intersection is essential for developing socially grounded and sustainable geoconservation strategies, which can also be incorporated into urban development programs or management programs.

CONCLUSION

This study presents the first systematic assessment of 24 LIGs along the central coast of Sonora, all of which possess scientific value and were evaluated for their educational and touristic potential, as well as degradation risk. Results show that eight sites have high scientific value, twelve strong educational potential, and six notable geotourism opportunities. LIGs with the highest scientific value are key to understanding the geological evolution of the Gulf of California, underscoring their national and international importance. Twelve sites face medium to high degradation risk, particularly those lacking formal protection and near expanding urban areas, highlighting the need for targeted, context-adapted conservation measures.

The findings also contribute valuable insights that can be integrated into existing conservation efforts in the region, which already include environmental education, monitoring, and citizen-science projects. Although these initiatives do not currently address geoheritage explicitly, they provide a solid foundation for its gradual and participatory inclusion with the support of local managers.

Beyond these local efforts, the formal recognition of geodiversity and geoheritage within legal frameworks remains a pending task. As shown in this study, their protection still depends largely on indirect mechanisms and collaboration with local stakeholders. Continued efforts are needed to promote their inclusion in public policies at all three administrative levels and to advance the establishment of national standards with unified criteria for the inventory, assessment, and conservation of LIGs. Implementing such measures would provide a stronger foundation for incorporating LIGs into management and planning programs, not as an option, but as a norm. In this process, institutions such as the Mexican Geological Survey (SGM), environmental agencies, and universities should play a leading role in developing studies, supporting policy development, and promoting geoheritage.

At the state level, Sonora's long-standing tradition of geological research—particularly in lithostratigraphy and mineral resources—has produced a robust scientific foundation that remains underutilized in geoheritage conservation. Universities have played a pivotal role in building this knowledge base and can now serve as key partners in expanding systematic geoheritage inventories and linking them to regional land-use and conservation planning. Such efforts would align with emerging geoscience paradigms that connect sustainability, education, and resource management through geoconservation.

Finally, the findings suggest that the region holds strong scientific, educational, and touristic potential. In the long term, this potential could support a candidacy for a UNESCO Global Geopark or other international designation, such as the recently launched Key Geoheritage Areas initiative of the International Union for Conservation of Nature (IUCN). However, given the current sociocultural context, such designations are not an immediate local priority. Strengthening education and community engagement remains essential to foster local interest and stewardship before pursuing any formal recognition. The active involvement of governmental environmental agencies (e.g., CONANP, SGM) will also be crucial to achieving this goal.

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SUPPLEMENTARY MATERIAL

Supplementary Tables S1 to S9 can be downloaded from the abstract's preview page of this paper at <https://www.rmccg.unam.mx>.

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