

# A multi-proxy approach for sediment variability assessment: Application along the Colombian Caribbean coast

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## ABSTRACT

Coastal sediments are sensitive recorders of environmental processes, yet interpretations based on granulometry alone capture only part of the information they preserve. This study presents the first regional-scale, multi-proxy characterization of beach sediments along the continental Caribbean coast of Colombia, integrating grain-size distribution, CIELAB colorimetry, and quantitative grain morphology for 59 sites distributed from the Guajira Peninsula (north) to the Gulf of Urabá (south). Granulometric analysis confirms a fine- to medium-sand, quartz-rich system shaped by persistent wave action, with localized coarse and gravelly enrichments in northern sectors. Colorimetric analysis shows that lightness ( $L^*$ , 41.8–68.5) and chroma ( $C^*$ , 1.4–25.4) behave as reproducible proxies for sediment maturity and oxidation: bright, saturated sediments correspond to well-washed, reworked sands, whereas dark, weakly saturated sediments reflect immature or locally sourced material. Grain morphology, quantified through Sobel-based angularity (0.027–0.109) and Powers roundness (2–5), reveals a strong inverse coupling ( $r \approx -0.83$ ) that records transport distance and mechanical abrasion. Sahu discriminant functions classify the system as dominantly beach and shallow-agitated-marine, with a subordinate fluvial signature in the north. Principal Component Analysis resolves a hierarchical structure dominated by an energy-maturity axis (PC1, ~43% of variance), followed by depositional variability (PC2, ~23%) and transport history (PC3, ~13%). Hierarchical clustering groups the samples into four statistical clusters, while the integrated proxies define five process-based facies (HE-M, HE-TM, ME-TM, ME-IM, PROX). The mismatch between four clusters and five facies is itself informative: end-member conditions are sharply resolved, whereas transitional states grade continuously and are compressed by clustering. We therefore argue that coastal sediment variability is best represented as a continuum governed by hydrodynamic energy and sediment supply, rather than as discrete categories. The framework is reproducible, low-cost, and transferable to other high-energy, sediment-limited coasts, with direct applications to monitoring, nourishment-compatibility assessment, and erosion management.

## 1. Introduction

Coastal sediments are fundamental components of littoral systems and act as dynamic interfaces among terrestrial, marine, and atmospheric processes (Leeder, 1982; Davis, 1985). Their physical, chemical, and biological properties integrate the combined influence of source lithology, transport pathways, and depositional energy, so that a sediment sample is, in effect, a compact archive of the processes that

delivered and reworked it (Ferraro et al., 2024). Reading that archive correctly is central to reconstructing coastal dynamics, diagnosing erosion, and designing management interventions.

Grain-size distribution is the most widely used sedimentological descriptor because it responds directly to the energy and transport regime of the depositional environment (Walgren et al., 2003; Syvitski et al., 2022). Coarse, well-sorted sediments typically indicate sustained high-energy conditions and efficient winnowing of fines, whereas finer,

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more poorly sorted material points to lower energy or mixed supply. Statistical parameters such as mean grain size, sorting, skewness, and kurtosis (Folk and Ward, 1957a; Folk, 1966) remain the pillar of environmental interpretation and feed discriminant schemes such as those of Sahu (1964) and Visser (1969).

In tropical settings such as the Caribbean coast of Colombia, the interpretive value of sediments is amplified by the interplay of climatic, oceanographic, and geomorphological controls (Sutherland and Lee, 1994). Strong and persistent trade-wind forcing, episodic high-energy events, and spatially irregular fluvial supply generate sharp gradients in texture and composition over short distances. These gradients make the region an excellent natural laboratory for testing whether sediment variability is organized by a small number of dominant controls.

Traditional coastal studies have nonetheless relied almost exclusively on granulometry as the primary interpretive tool (Bray et al., 2024; Haque et al., 2026). While grain-size parameters are powerful, they are also non-unique: distinct combinations of source, transport, and reworking can yield similar distributions, and grain size alone cannot distinguish a mature, far-travelled sand from a locally derived sand that happens to share the same modal class. This ambiguity limits process-based interpretation, particularly in dynamic systems where mixing and reworking are pervasive.

A first major limitation of the granulometric-only approach is the omission of optical properties, which carry independent information on composition, mineralogy, and weathering state (Pranzini et al., 2010, 2016). Within the CIELAB color space, lightness ( $L^*$ ), the red–green axis ( $a^*$ ), the yellow–blue axis ( $b^*$ ), and the derived chroma ( $C^*$ ) and hue angle ( $h^\circ$ ) respond to mineral coatings, iron-oxide enrichment, organic matter, and moisture (Azzali et al., 2011; Vodyanitskii and Savichev, 2017; Razali et al., 2025). Because these signals are largely decoupled from grain size, colorimetry can resolve maturity contrasts that texture alone leaves hidden.

A second limitation is the inattention of grain morphology, despite its direct link to transport history (Słowik-Opoka et al., 2026). Angularity and roundness record the cumulative mechanical work done on a grain during transport: repeated collisions progressively abrade edges, so that shape evolves systematically from angular, proximal material toward rounded, far-travelled material (Kelly, 1983; Gresina et al., 2023). Morphology therefore provides a transport-distance proxy that is conceptually independent of both texture and color.

Recent work has begun to combine optical and morphological descriptors with conventional granulometry as complementary proxies (Asensio-Montesinos et al., 2020; Nichols et al., 2023). The promise of this multi-proxy strategy is that proxies which capture partly independent aspects of the sedimentary system can, when integrated, constrain provenance and process far more tightly than any single descriptor. What has been missing is a regional test of this strategy in a high-energy tropical system, framed explicitly around the structure of sediment variability rather than around isolated parameters.

Along the Colombian Caribbean, sediment research remains limited in both spatial coverage and methodological integration. Existing studies have largely focused on individual sectors or on single descriptors (Rangel-Buitrago et al., 2018, 2022; Restrepo et al., 2013), and no work has yet combined texture, color, and morphology at the regional scale. This gap is significant because the coast is both economically important and chronically eroding, so that a reproducible, transferable characterization framework has immediate management value.

The objective of this study is to develop an integrated understanding of sediment variability along the Colombian Caribbean coast using a multi-proxy framework. Specifically, we (i) characterize regional granulometric, colorimetric, and morphological patterns across 59 sites; (ii) test  $L^*$  and  $C^*$  as quantitative proxies for maturity and oxidation, and angularity and roundness as proxies for transport history; (iii) identify the dominant gradients structuring the system through correlation, PCA, and clustering; and (iv) settle statistical groupings with process-based

facies. We hypothesize that variability is governed primarily by a single energy–maturity gradient and is best described as a continuum rather than a set of discrete classes.

## 2. The Caribbean coast of Colombia

The continental Caribbean coast of Colombia extends approximately 1600 km along the northern margin of South America, from the Gulf of Urabá in the west to the Guajira Peninsula in the east (Fig. 1; Correa and Morton, 2010). This margin spans a wide range of geomorphic and climatic settings, from humid, sediment-rich deltaic sectors in the southwest to arid, sediment-limited sectors in the northeast, providing strong environmental contrasts over a single littoral system.

Coastal morphology is dominated by sandy beaches, interspersed with rocky headlands, cliffs, and dune fields (Anfuso et al., 2015). Sandy beaches are the most extensive landform and are typically composed of fine to medium quartz-rich sands forming long, continuous shorelines (Rangel-Buitrago et al., 2013, 2026). Headlands and cliffs locally interrupt these beaches and modulate wave exposure, creating alternating exposed and sheltered compartments that strongly influence sediment texture and reworking.

Dune systems occur particularly in sediment-limited sectors, where aeolian processes rework beach sand into well-sorted backshore accumulations (Rangel-Buitrago et al., 2023). These dunes act as both temporary sinks and secondary sources, returning fine, well-sorted quartz sand to the beach during high-energy events and thereby contributing to the optical and textural maturity of adjacent deposits.

The oceanographic regime is high-energy and dominated by persistent northeasterly trade winds and wave-driven transport (Bernal et al., 2016). Trade winds prevail for most of the year and intensify during the dry season, generating sustained longshore currents (Urbano-Latorre et al., 2023). Episodic cold fronts and tropical systems superimpose high-energy events on this background forcing (Ortiz, 2012; Ortiz et al., 2013), driving pulses of reworking and cross-shore exchange.

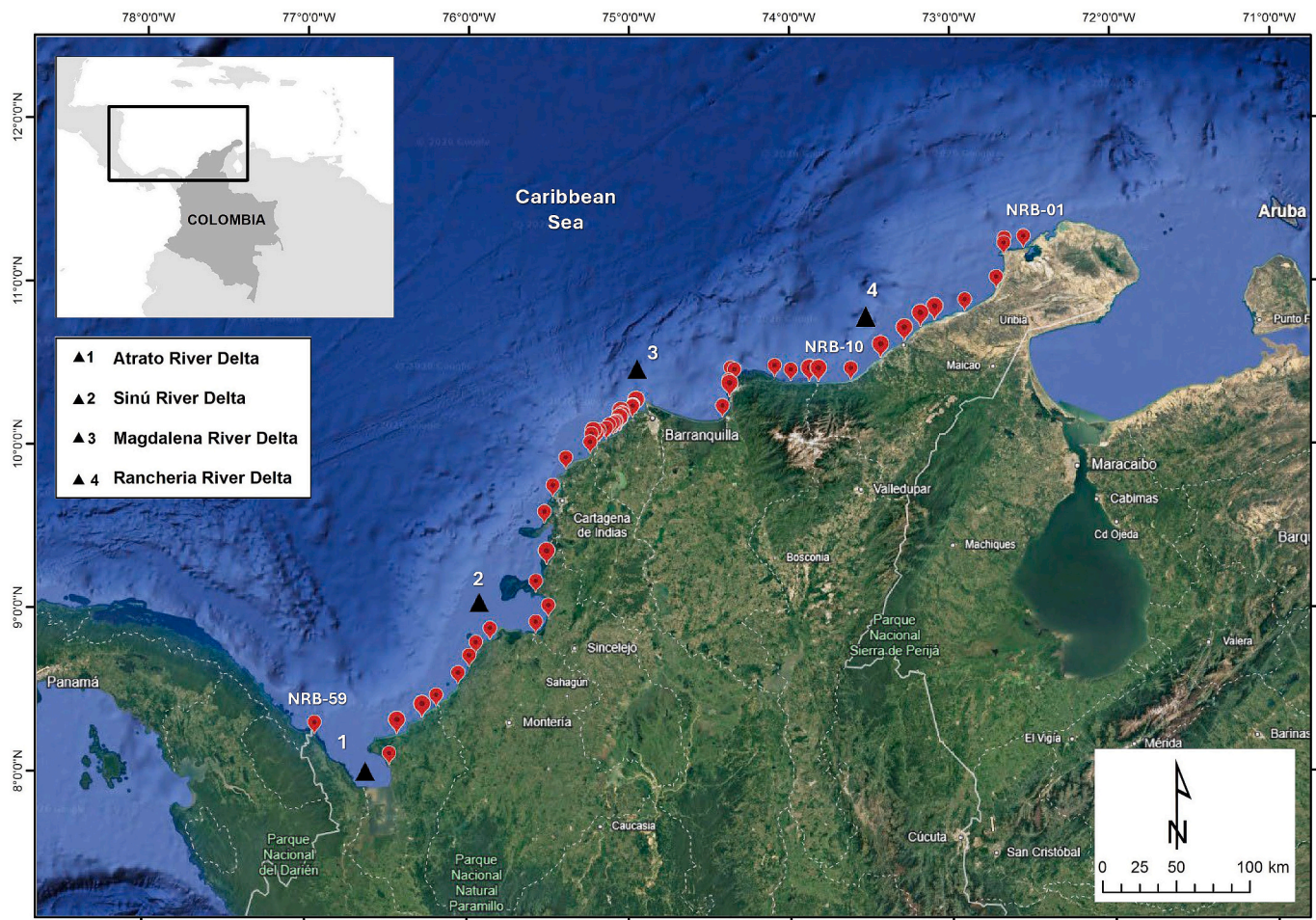
The coast is microtidal, with semidiurnal ranges generally between 0.3 and 0.4 m, so that tidal forcing is minor compared with wave action (Torres and Tsimplis, 2012). Consequently, beach morphodynamics are governed primarily by wave energy and its modulation by coastal configuration: open coastlines experience direct wave impact, while headland-protected sectors operate under reduced energy. These contrasts apply a first-order control on sediment sorting, maturity, and morphology and underline the exposure classification used in this study.

Sediment supply is dominated by fluvial inputs and coastal cliff erosion, with availability partly controlled by seasonal wave regimes (Rangel-Buitrago et al., 2015). The Magdalena River is by far the most important source, historically delivering on the order of 140–170 million tons of sediment per year to the Caribbean (Restrepo et al., 2015; Restrepo and Escobar, 2018; Restrepo López et al., 2017). The Atrato, Sinú, and Ranchería rivers provide additional, regionally important contributions (Fig. 1).

Several sectors are nonetheless sediment-limited, including insular areas and stretches between Cartagena and the southern Morrosquillo Gulf, where supply is naturally low or has been reduced by engineering interventions. The Bocas de Ceniza jetties at the Magdalena mouth, in particular, have diverted much of the river's load directly to the deep Magdalena turbidite system (Ercilla et al., 2002a, 2002b; Martínez et al., 1990), curtailing along-shelf delivery to adjacent beaches (Gracia et al., 2024).

These supply disruptions have contributed to chronic erosion, with shoreline retreat exceeding  $1\text{ m yr}^{-1}$  in several sectors (Rangel-Buitrago et al., 2015). Additional pressures from urbanization, port infrastructure, and tourism (Rangel-Buitrago, 2023; Williams et al., 2018) make the coast a representative example of a high-energy, sediment-limited tropical system in which internal recycling and longshore transport increasingly govern sediment behavior, the very conditions under which a sensitive, multi-proxy characterization is most valuable.





**Fig. 1.** Location of the study area along the Colombian Caribbean coast showing the distribution of the 59 sampled sites. Major fluvial sediment sources (Atrato, Sinú, Magdalena, and Ranchería river deltas) are indicated, highlighting regional sediment supply controls.

### 3. Material and methods

#### 3.1. Sampling design

Surface sediment was sampled at 59 beach sites distributed along the continental Caribbean coast of Colombia (Fig. 1; Table 1). Sites were selected to provide broad spatial coverage and to represent the main geomorphological, oceanographic, and anthropogenic settings of the margin, spanning rural, village, urban, resort, remote, artificial, and protected typologies and both exposed and sheltered wave conditions (Table 1).

Sampling was conducted under stable weather, avoiding periods of extreme hydrometeorological activity, to minimize short-term disturbance and maximize inter-site comparability. At each site a 1 m × 1 m quadrat was deployed on the foreshore, in the active swash-influenced zone, ensuring that the sampled material represented the contemporary, wave-reworked sediment population rather than relict or storm-deposited layers.

Within each quadrat, approximately 1 kg of surface sediment was collected from the upper 2–3 cm using clean plastic scoops, placed in labeled polyethylene bags, and handled to avoid contamination and preserve original characteristics. Sample identifiers follow a north-to-south sequence (NRB-1 to NRB-59), enabling the spatial trends examined throughout this study.

#### 3.2. Granulometric analysis

In the laboratory, samples were air-dried at room temperature to preserve mineral integrity and avoid thermally induced disaggregation. Dried samples were gently disaggregated and processed by standardized dry sieving through a nested column spanning the gravel-to-fine-sand range (2, 1, 0.5, 0.25, 0.125, and 0.063 mm), with the fraction finer than 0.063 mm collected in the pan. Dry sieving was preferred over wet sieving because the analyzed sediments are almost exclusively clean, quartz-rich sands with negligible mud content (generally <1%), a condition under which wet sieving offers no analytical advantage. To minimize potential mechanical alteration of grains, disaggregation was performed gently by hand, no grinding or forced crushing was applied, and sieving times and shaking intensity were standardized across all samples. The mechanical resistance of the dominant quartz lithology further limits grain breakage or edge modification during handling, and inspection of representative grains under magnification before and after sieving revealed no evidence of fracturing. Wet sieving remains advisable for mud-rich or aggregate-prone sediments, but for the sand-dominated samples analyzed here dry sieving provides accurate, reproducible results without compromising grain integrity.

The proportion retained on each sieve was determined by weight on a precision balance ( $\pm 0.01$  g) and expressed as a percentage of total sample mass. Grain-size distributions were characterized using the graphical statistics of Folk and Ward (1957b), yielding median grain size ( $M_z$ ), sorting ( $\sigma$ ), skewness ( $Sk$ ), and kurtosis ( $K$ ). All parameters were computed in GRADISTAT (Blott and Pye, 2001) to ensure consistency

**Table 1**

Classification of the 59 sampled coastal sites along the Caribbean coast of Colombia according to their typology and exposure.

| Sample ID | Site                                             | Typology           | Exposure  |
|-----------|--------------------------------------------------|--------------------|-----------|
| NRB-1     | Yokuyokutshi, Puerto Bolívar-La Guajira          | Rural              | Exposed   |
| NRB-2     | Pilón de Azúcar-La Guajira                       | Rural              | Sheltered |
| NRB-3     | Cabo de La Vela-La Guajira                       | Mixed/transitional | Sheltered |
| NRB-4     | Solipa-La Guajira                                | Remote             | Exposed   |
| NRB-5     | Playas de Manaure, Manaure-La Guajira            | Mixed/transitional | Exposed   |
| NRB-6     | Playa El Pájaro, El Pájaro-La Guajira            | Village            | Exposed   |
| NRB-7     | Playa de Mayapo, Mayapo-La Guajira               | Mixed/transitional | Exposed   |
| NRB-8     | Playa de Riohacha, Riohacha-La Guajira           | Urban Low          | Exposed   |
| NRB-9     | Playa de Camarones, Boca de Camarones-La Guajira | Rural              | Exposed   |
| NRB-10    | Playa Dibulla, Dibulla-La Guajira                | Village            | Exposed   |
| NRB-11    | Playa Palomino, Palomino-La Guajira              | Rural              | Exposed   |
| NRB-12    | Playa Los Coquitos, Avd. Sta. Marta-Palomino     | Protected-Open     | Exposed   |
| NRB-13    | Playa Buritaca, Buritaca-Magdalena               | Village            | Exposed   |
| NRB-14    | Playa Los Ángeles, Vda. Los Naranjos, Sta. Marta | Remote             | Exposed   |
| NRB-15    | Playa Taganga, Sta. Marta-Magdalena              | Mixed/transitional | Sheltered |
| NRB-16    | Playa Los Cocos, Sta. Marta-Magdalena            | Urban Low          | Sheltered |
| NRB-17    | Playa Salguero, Sta. Marta-Magdalena             | Urban Low          | Sheltered |
| NRB-18    | Playa Bello Horizonte, Sta. Marta-Magdalena      | Urban Low          | Sheltered |
| NRB-19    | Pueblo Viejo-Magdalena                           | Village            | Exposed   |
| NRB-20    | Punta Roca-Atlantico                             | Urban Low          | Exposed   |
| NRB-21    | Salgar-Atlantico                                 | Village            | Exposed   |
| NRB-22    | Pradomar - Resort-Atlantico                      | Resort             | Exposed   |
| NRB-23    | Pradomar - Urban-Atlantico                       | Urban Low          | Exposed   |
| NRB-24    | Puerto Colombia - North-Atlantico                | Urban Low          | Exposed   |
| NRB-25    | Puerto Colombia - Urban                          | Urban Low          | Exposed   |
| NRB-26    | Puerto Velero - Exposed-Atlantico                | Remote             | Exposed   |
| NRB-27    | Puerto Velero -Resort-Atlantico                  | Resort             | Sheltered |
| NRB-28    | Puerto Velero -Punta Velero-Atlantico            | Mixed/transitional | Sheltered |
| NRB-29    | Puerto Velero - Mirador-Atlantico                | Village            | Sheltered |
| NRB-30    | Caño Dulce-Atlantico                             | Village            | Sheltered |
| NRB-31    | Playa Mendoza-Atlantico                          | Resort             | Sheltered |
| NRB-32    | Palmarito-Atlantico                              | Village            | Sheltered |
| NRB-33    | Playa Linda-Atlantico                            | Village            | Exposed   |
| NRB-34    | Santa Veronica Cajacooi-Atlantico                | Resort             | Exposed   |
| NRB-35    | Santa Veronica-Atlantico                         | Village            | Sheltered |
| NRB-36    | Salinas Del Rey-Atlantico                        | Rural              | Sheltered |
| NRB-37    | Loma De Piedra-Atlantico                         | Rural              | Sheltered |
| NRB-38    | Aguamarina-Atlantico                             | Resort             | Sheltered |
| NRB-39    | Bocatocinos-Atlantico                            | Rural              | Exposed   |
| NRB-40    | Punta Astilleros-Atlantico                       | Rural              | Sheltered |
| NRB-41    | Salinas De Galerazamba-Atlantico                 | Remote             | Exposed   |
| NRB-42    | Galerazamba-Bolivar                              | Rural              | Sheltered |
| NRB-43    | Loma De Arena-Bolivar                            | Rural              | Sheltered |
| NRB-44    | Arroyo De Piedra-Bolivar                         | Resort             | Sheltered |
| NRB-45    | Cartagena-Bolivar                                | Artificial         | Exposed   |
| NRB-46    | Playa Blanca-Bolivar                             | Protected-Open     | Exposed   |
| NRB-47    | Sabanetica-Sucre                                 | Fishing/Community  | Sheltered |
| NRB-48    | Sanguaré-Sucre                                   | Artificial         | Sheltered |
| NRB-49    | Tolú-Sucre                                       | Artificial         | Sheltered |
| NRB-50    | Coveñas-Sucre                                    | Urban Low          | Sheltered |
| NRB-51    | San Bernardo Del Viento-Cordoba                  | Fishing/Community  | Exposed   |
| NRB-52    | Moñitos-Cordoba                                  | Rural              | Exposed   |
| NRB-53    | Rio Cedro-Cordoba                                | Fishing/Community  | Sheltered |
| NRB-54    | Puerto Escondido-Cordoba                         | Rural              | Sheltered |
| NRB-55    | Arboletes-Antioquia                              | Village            | Sheltered |
| NRB-56    | Playa San Juan-Antioquia                         | Rural              | Exposed   |

**Table 1 (continued)**

| Sample ID | Site                     | Typology   | Exposure  |
|-----------|--------------------------|------------|-----------|
| NRB-57    | Mulatos-Antioquia        | Rural      | Exposed   |
| NRB-58    | Sur De Necoclí-Antioquia | Artificial | Sheltered |
| NRB-59    | Capurganá-Antioquia      | Village    | Exposed   |

and reproducibility, and samples were additionally partitioned into gravel, sand, and mud fractions for textural classification.

Granulometric variables served both as primary descriptors of depositional conditions and as inputs to the depositional indices and multivariate analyses described below. Particular attention was paid to polymodal distributions, which can indicate episodic transport, mixing of sediment populations, or multiple sources (Kasper-Zubillaga et al., 2022).

### 3.3. Colorimetric analysis

Sediment color was quantified in the CIELAB color space, which describes color through three independent dimensions: lightness ( $L^*$ ), the red–green axis ( $a^*$ ), and the yellow–blue axis ( $b^*$ ). CIELAB is widely used in sedimentology and soil science because it is perceptually uniform and links directly to composition, oxidation, and organic content (Pranzini et al., 2010; Palechor-Tróchez et al., 2018).

Prior to analysis, each sample was homogenized and spread in a uniform layer about 1 cm thick on a matte white background. Images were acquired in a controlled photo lightbox with standardized LED illumination and fixed camera geometry, eliminating variable ambient lighting and ensuring comparability across samples. This control is essential, because uncontrolled illumination is the principal source of error in image-based colorimetry.

Digital images were processed in ImageJ. For each sample, a central rectangular region of interest — covering most of the imaged sample surface (several square centimeters, encompassing thousands of grains) and excluding the outer margins to avoid edge and vignetting effects — was defined, and mean  $L^*$ ,  $a^*$ , and  $b^*$  values were extracted over this area. The reported values are therefore area-averaged measurements over a large grain population rather than single-point readings. From these primaries, two derived variables were computed: chroma,  $C^* = (a^{*2} + b^{*2})^{1/2}$ , representing color saturation and associated with oxidation intensity and mineral enrichment; and hue angle,  $h^\circ = \arctan(b^*/a^*)$ , describing the dominant spectral character.

Standardized illumination, calibrated imaging, and replicated measurements ensure high reproducibility and cross-site comparability. The resulting colorimetric dataset was then integrated with granulometric and morphological variables, allowing color to be tested explicitly as a maturity proxy rather than treated as a descriptive attribute. Regarding the potential influence of the time elapsed between sampling and analysis, all colorimetric measurements were performed on air-dried, homogenized material within a consistent time window after collection, with samples stored in sealed, opaque polyethylene bags at room temperature until analysis. Air-drying standardizes moisture content, one of the main controls on apparent lightness, while dark, sealed storage limits photochemical and oxidative alteration of organic or iron-oxide coatings prior to imaging. Because the studied sands are quartz-dominated and generally organic-poor, post-sampling color drift is expected to be minor; in any case, the uniform storage protocol and fixed sampling-to-analysis workflow ensure that any residual alteration affects all samples equally and therefore does not bias inter-site comparisons.

### 3.4. Grain morphology

Grain morphology was characterized through two complementary quantitative descriptors, angularity and roundness, which were then



used to infer transport history and mechanical reworking. Integrating a quantitative, image-based angularity index with a classical roundness scale is a central methodological contribution of this study, because the two descriptors capture different scales of grain shape.

Angularity was quantified by Sobel edge detection (Ravichandran et al., 2025). The high-resolution images acquired for colorimetry were converted to grayscale and processed with a Sobel operator; the mean edge intensity was used as an angularity index, with higher values indicating sharper, more abundant edges (more angular grains) and lower values indicating smoother outlines (more rounded grains). Because the index is computed automatically over a large grain population, it provides an objective, reproducible measure that is insensitive to operator bias.

Roundness was assessed on the Powers (1953) scale, which ranks grains from very angular (1) to well rounded (6). For each sample, representative grains were inspected under magnification and assigned an average roundness class. Roundness reflects the cumulative, macro-scale rounding of grain corners and therefore complements the edge-scale information captured by the Sobel index.

The combined use of Sobel-derived angularity and Powers-based roundness provides a complementary characterization of grain morphology. While angularity captures fine-scale edge sharpness through quantitative image analysis, roundness reflects broader morphological evolution through established sedimentological classification.

3.5. Environmental classification framework

To interpret variability in a process-oriented manner, we developed a classification framework integrating granulometric, optical, and morphological descriptors (Table 2). The framework defines five environmental categories along a single energy–maturity gradient: High Energy–Mature (HE-M), High Energy–Transitional Maturity (HE-TM), Moderate Energy–Transitional Maturity (ME-TM), Moderate Energy–Immature (ME-IM), and Proximal Source Dominated (PROX).

The criteria rest on three primary variables. Angularity (Sobel index) serves as a transport-distance and abrasion proxy, with lower values indicating prolonged reworking. Roundness (Powers scale) corroborates this signal at the grain-corner scale. Optical maturity, expressed through L\* and C\*, captures the degree of washing, oxidation, and removal of coatings, with higher values denoting more mature sediment (Table 2).

Samples were evaluated jointly against these criteria. HE-M sediments combine low angularity, high roundness, and elevated L\* and C\*, indicating sustained high-energy reworking; the HE-TM, ME-TM, and ME-IM categories represent successively lower maturity and higher angularity; and PROX sediments show extreme angularity and low roundness (i.e., minimal textural maturity) together with anomalous color, indicating minimal transport and strong lithological control. Crucially, the framework is designed to describe positions along a continuum rather than mutually exclusive bins. Throughout this study, “mature” and “immature” are used in the classical textural sense of Folk

(1951), denoting the degree to which a sediment has been winnowed of fines, sorted, and its grains rounded during transport and reworking. Where the terms “optical maturity” or “optically mature/immature” appear, they designate only the colorimetric expression of that textural state — the elevated L\* and C\* produced by washing, removal of coatings, and oxidation of stable mineral surfaces — and are not intended as an independent evolutionary concept; color is treated strictly as a proxy for, not a redefinition of, sedimentological maturity.

3.6. Depositional indices

Depositional environments were inferred using the discriminant functions of Sahu (1964), which assume that grain-size statistics encode the energy and medium of deposition. Three functions (Y1, Y2, Y3) were computed from mean grain size (Mz), sorting (σ), skewness (Sk), and kurtosis (K).

$$Y_1 = -3.5688Mz + 3.7016\sigma^2 - 2.0766Sk + 3.1135K$$

$$Y_2 = 15.6534Mz + 65.709\sigma^2 + 18.1071Sk + 18.5043K$$

$$Y_3 = 0.2852Mz - 8.7604\sigma^2 - 4.8932Sk + 0.0483K$$

The first function (Y1) distinguishes aeolian from beach environments, with values below −2.7411 indicating aeolian deposition and higher values indicating beach conditions. The second (Y2) separates beaches from shallow-agitated-marine environments, with values above 65.365 indicating shallow agitated marine conditions. The third (Y3) discriminates shallow-marine from fluvial (turbidity-influenced) deposition, refining the depositional interpretation.

The indices were computed for all samples and interpreted jointly with granulometric, optical, and morphological variables. As discussed below, Sahu’s functions are valuable for first-order classification but, being based solely on grain-size statistics, tend to force continuous variability into discrete categories, a limitation our multi-proxy data are well positioned to expose.

3.7. Statistical analysis

Statistical analyses were used to explore relationships among variables and to identify the dominant gradients structuring sediment variability. All quantitative variables, granulometric parameters (Mz, σ, Sk, K), colorimetric parameters (L\*, a\*, b\*, C\*, h°), morphological descriptors (angularity, roundness), and Sahu indices (Y1, Y2, Y3), were standardized (z-scores) prior to multivariate analysis to remove scale effects.

Pairwise relationships were assessed with Pearson correlation to quantify the degree of coupling among texture, color, morphology, and depositional indices. We emphasize at the outset that correlation strength varies by proxy pair: within-domain morphological coupling is strong, whereas cross-domain optical–textural coupling is weaker but

**Table 2**  
Process-based environmental classification framework based on integrated sediment properties.

| Category                                        | Energy level | Angularity (Sobel)          | Roundness (Powers)  | L* (Lightness)        | C* (Chroma)        | Sedimentological interpretation                                                   |
|-------------------------------------------------|--------------|-----------------------------|---------------------|-----------------------|--------------------|-----------------------------------------------------------------------------------|
| HE-M (High energy – Mature)                     | High         | Low (<0.040)                | High (4–6)          | High (>60)            | High (>12)         | Well-washed, quartz-rich, highly reworked sediments under persistent wave action. |
| HE-TM (High energy – Transitional maturity)     | High         | Low–Moderate (0.040–0.055)  | Moderate–High (3–5) | Moderate–High (55–60) | Moderate (8–12)    | High-energy environments with partial reworking and mixed sediment sources.       |
| ME-TM (Moderate energy – Transitional maturity) | Moderate     | Moderate (0.050–0.070)      | Moderate (3–4)      | Moderate (50–58)      | Moderate (7–11)    | Variable energy conditions, incomplete sorting, transitional transport regimes.   |
| ME-IM (Moderate energy – Immature)              | Moderate     | Moderate–High (0.060–0.090) | Low–Moderate (2–3)  | Low–Moderate (45–55)  | Low–Moderate (5–9) | Limited reworking, influence of local inputs, partial sorting.                    |
| PROX (Proximal source dominated)                | Low–Variable | High (>0.090)               | Low (1–2)           | Low (<50)             | Variable           | Minimal transport, strong lithological control, local sediment supply.            |

directionally consistent. This pattern is expected when proxies capture partly independent facets of the system, and we interpret it accordingly rather than overstating cross-domain correlations.

Principal Component Analysis (PCA) was applied to the standardized dataset to reduce dimensionality and identify the main gradients of variability. Component loadings were examined to attribute each axis to a physical process. Hierarchical clustering (Ward's minimum-variance method, Euclidean distance) was then used to group samples by overall multivariate similarity, producing a dendrogram from which an optimal partition was selected. PCA and clustering were treated as complementary: the former describes continuous gradients, the latter discrete groupings, and their comparison underpins the continuum-versus-discrete analysis that follows.

## 4. Results and discussion

### 4.1. Regional sediment patterns: Texture, color, and grain morphology

The granulometric composition of the 59 sites confirms a strong dominance of sand and, with it, the prevalence of high-energy, wave-dominated deposition across the region (Fig. 2). Sand fractions account for most of the sample mass at most sites (exceeding 95%), with mud almost universally negligible, consistent with efficient winnowing of fines under sustained wave action.

Gravel content is spatially variable. Most sites contain less than 1% gravel, but localized enrichments occur in northern sectors, particularly in La Guajira and Magdalena, where several sites (e.g., NRB-1, NRB-3, NRB-14, NRB-20) carry appreciable gravel and very coarse sand (Table 3, Fig. 2). These coarse enrichments coincide with proximity to coarse fluvial or cliff sources and with the highest-energy exposed settings, where sustained hydrodynamic sorting winnows the finer fractions and leaves a residual enrichment of the coarsest grains.

Across most of the coast, the 0.250 mm and 0.125 mm fractions dominate, frequently exceeding 60–80% of the total (Table 3, Fig. 2). This fine- to medium-sand matrix is the textural signature of a mature, wave-graded system. Median grain size ( $M_z$ ) ranges from  $-0.69 \phi$  (very coarse sand) to  $3.19 \phi$  (very fine sand), but most samples cluster in the fine-sand domain ( $\sim 2.0$ – $2.7 \phi$ ), indicating strong regional textural consistency despite local extremes (Table 3, Fig. 2).

Sorting spans well-sorted to poorly sorted values ( $\sigma \approx 0.25$ – $1.34$ ), with a clear majority in the moderately-well-sorted to well-sorted range, again pointing to effective hydraulic grading. The best-sorted samples occur in the south-central sectors (e.g., Córdoba), whereas the most poorly sorted occur where coarse fluvial input or mixing is strongest in the north (Table 3, Fig. 3).

Skewness is predominantly negative (coarse-skewed; mean  $Sk \approx -0.36$ ), indicating selective removal of fines and enrichment in coarser particles under energetic conditions. Extreme skewness values (e.g., NRB-26, NRB-28, NRB-47) flag localized departures from the regional norm, typically where proximal supply or episodic transport disrupts hydraulic equilibrium (Fig. 3). Kurtosis is highly variable ( $K \approx 0.86$ – $18.36$ ) and frequently leptokurtic, consistent with the dominance of a single, well-sorted mode punctuated by occasional secondary populations.

The combined textural classification and granulometric patterns allows to define the Colombian Caribbean coast as a predominantly fine- to medium-sand-dominated system, controlled by wave-driven processes and longshore transport. Localized deviations, particularly in gravel enrichment and statistical parameters, reflect the influence of geomorphological controls, sediment supply variability, and episodic high-energy events.

Colorimetric analysis reveals marked variability in sediment optical properties across the 59 sites, reflecting differences in composition, transport history, and depositional conditions (Table 4; Fig. 4). Lightness ( $L^*$ ) ranges from 41.8 to 68.5 (mean  $\sim 57.5$ ), spanning dark, immature sediments to bright, well-washed sands and providing a

continuous measure of optical maturity.

The  $a^*$  parameter is predominantly negative ( $-3.03$  to  $+1.22$ ; mean  $\sim -1.5$ ), with most values between  $-2.5$  and  $-1.0$ , indicating a consistent slight greenish bias typical of quartz-rich sands with minor mafic or organic influence. Likely contributors to this subtle darkening include mafic and heavy minerals shed from the igneous and metamorphic terrains of the Sierra Nevada de Santa Marta and the Guajira basement, together with minor organic films in lower-energy, sheltered sectors. It must be noted, however, that CIELAB parameters alone cannot unambiguously discriminate organic matter from mafic or heavy-mineral grains, since both darken the sediment and lower chroma; such attribution requires complementary compositional evidence (e.g., microscopy or geochemistry), and color is therefore interpreted here strictly as a bulk optical proxy. The limited spread of  $a^*$  indicates that the red–green axis carries little discriminating power here; the optical signal is dominated instead by the yellow–blue axis and saturation.

The  $b^*$  component and the derived chroma ( $C^*$ ) show the strongest optical variability, with  $b^*$  from  $-0.65$  to  $25.32$  and  $C^*$  from  $1.38$  to  $25.35$  (Table 4). High  $C^*$  values denote strongly yellow, oxidized, iron-coated sands, whereas low  $C^*$  values mark weakly colored, less reworked material with reduced oxide coatings. (Moisture is a further general control on apparent color, but because all samples were measured air-dried under identical conditions, it does not contribute to the variability reported here.) This range makes  $C^*$  the most informative single optical descriptor in the dataset.

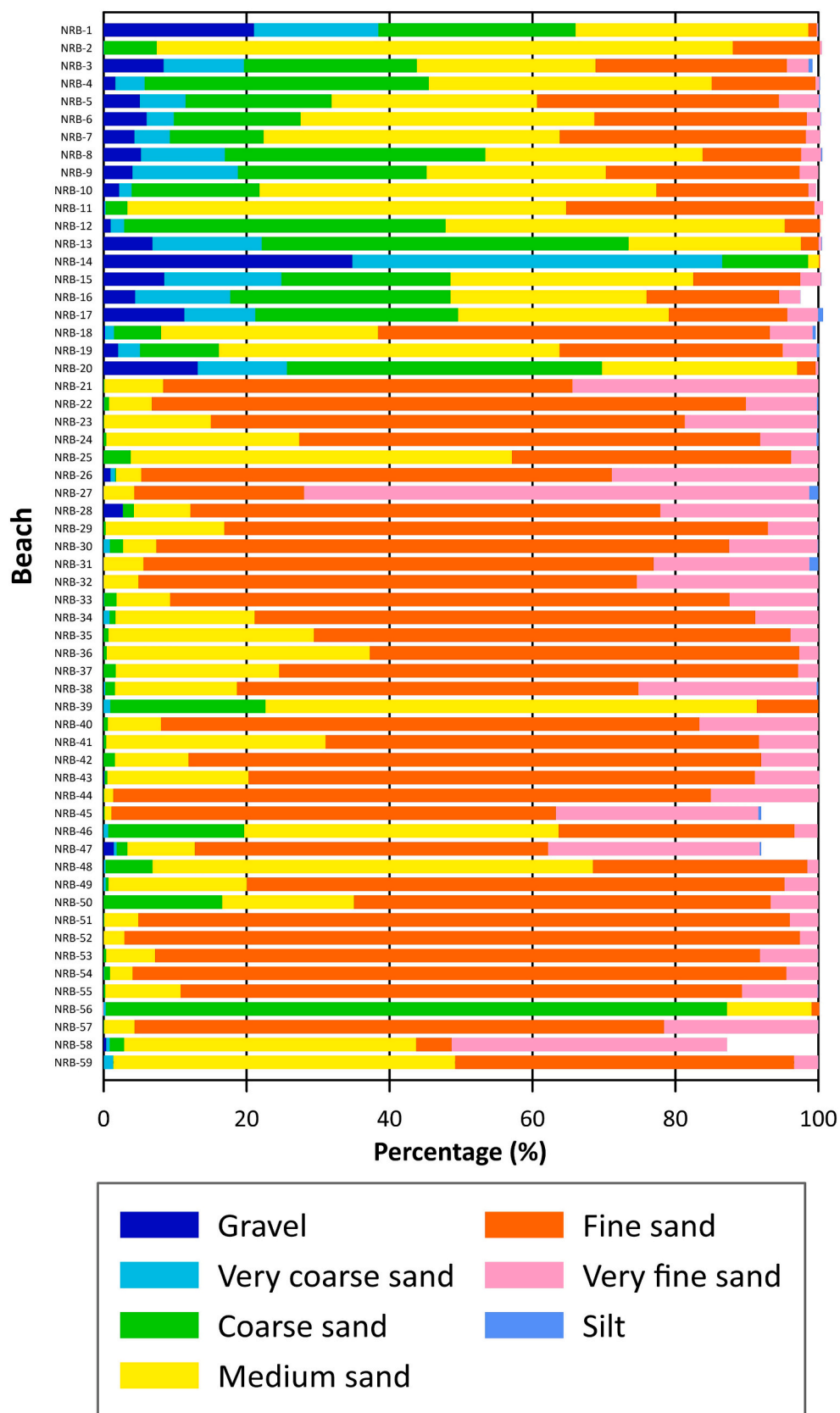
Hue angle ( $h^\circ$ ) clusters mostly between  $90^\circ$  and  $105^\circ$ , consistent with yellow-dominated, quartz-rich beach sands. Extreme values such as  $h^\circ \approx 332^\circ$  (NRB-26) are diagnostic of anomalous, dark, weakly saturated sediments dominated by lithic or heavy-mineral components and identify the same proximal end-member that the morphological and granulometric data isolate.

To synthesize these patterns, we defined five optical clusters (C1–C5) using  $L^*$  and  $C^*$  thresholds (Table 5). The dominant cluster (C3 – Intermediate) comprises most samples and is characterized by moderate lightness ( $L^* \approx 52$ – $58$ ) and chroma ( $C^* \approx 7$ – $12$ ), reflecting transitional sediment maturity and widespread coastal homogenization. High-maturity clusters (C1 and C2), defined by elevated  $L^*$  and  $C^*$  values, are primarily associated with exposed northern sectors and indicate intense wave reworking and strong oxidative conditions. In contrast, low-maturity clusters (C4) and anomalous cases (C5) are restricted to specific sites, particularly in sheltered environments such as the Puerto Velero sector, where reduced hydrodynamic energy, organic coatings, or localized sediment sources influence sediment optical properties. This optical classification mirrors the energy–maturity gradient recovered independently by texture and morphology.

Spatially, northern sectors (La Guajira and Magdalena) show higher  $L^*$  and  $C^*$ , indicating brighter, more oxidized sediments; central sectors (Atlántico) show the greatest variability, including both mature and anomalous signatures; and southern sectors are intermediate. The integration of colorimetric parameters with cluster classification demonstrates that sediment color is governed by hydrodynamic energy, transport, and maturity rather than by composition alone (Pranzini et al., 2016), establishing the empirical basis for treating  $L^*$  and  $C^*$  as maturity proxies.

Grain morphology shows clear spatial and process-driven structure across the coast (Table 4; Fig. 5). Angularity (Sobel index) ranges from  $0.027$  to  $0.109$ , with low values concentrated in exposed northern sectors and the highest values in sheltered, transitional, or proximally supplied settings, defining a coherent transport-distance gradient.

Roundness (Powers scale) spans the angular-to-rounded range (classes 2–5), with neither very-angular (1) nor well-rounded (6) end-members represented. Rounded grains (classes 4–5) dominate northern high-energy sectors, particularly La Guajira and northern Magdalena, while angular grains (class 2) are common in central and southern sectors where transport is shorter or supply more proximal. Notably, class 2 is the single most frequent roundness category in the dataset,



**Fig. 2.** Grain-size composition of sediments across all sampling sites expressed as percentage of gravel, sand fractions, and silt. The figure illustrates the dominance of sandy fractions and spatial variability in sediment texture along the coast.



**Table 3**

Granulometric composition and associated statistical parameters for 59 coastal sediment samples collected from beaches along the Caribbean coast Colombia.

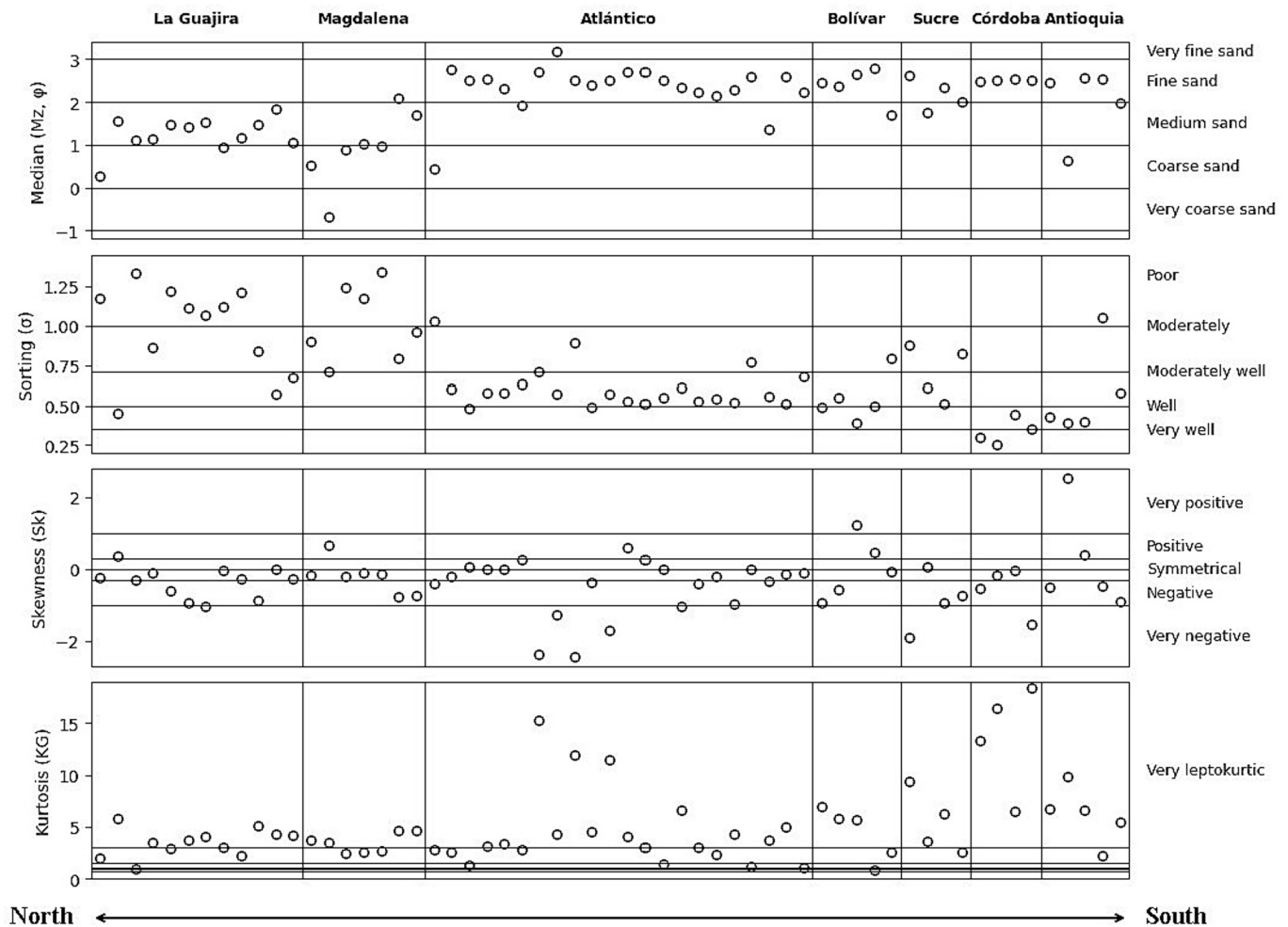
| Sample ID | 2 mm  | 1 mm  | 0.5 mm | 0.250 mm | 0.125 mm | 0.063 mm | <0.063 mm | Median | Sorting | Skewness | Kurtosis |
|-----------|-------|-------|--------|----------|----------|----------|-----------|--------|---------|----------|----------|
| NRB-1     | 21.05 | 17.38 | 27.60  | 32.55    | 1.19     | 0.16     | 0.07      | 0.26   | 1.17    | −0.23    | 1.92     |
| NRB-2     | 0.00  | 0.05  | 7.38   | 80.58    | 12.19    | 0.28     | 0.01      | 1.55   | 0.45    | 0.38     | 5.75     |
| NRB-3     | 8.39  | 11.23 | 24.18  | 25.02    | 26.79    | 3.02     | 0.55      | 1.12   | 1.33    | −0.32    | 0.90     |
| NRB-4     | 1.63  | 4.10  | 39.76  | 39.57    | 14.54    | 0.55     | 0.09      | 1.13   | 0.86    | −0.12    | 3.48     |
| NRB-5     | 5.07  | 6.39  | 20.44  | 28.73    | 33.85    | 5.60     | 0.16      | 1.47   | 1.22    | −0.62    | 2.95     |
| NRB-6     | 6.04  | 3.78  | 17.73  | 41.08    | 29.75    | 1.93     | 0.08      | 1.41   | 1.11    | −0.93    | 3.75     |
| NRB-7     | 4.33  | 4.93  | 13.11  | 41.44    | 34.44    | 1.99     | 0.02      | 1.53   | 1.07    | −1.04    | 4.01     |
| NRB-8     | 5.25  | 11.71 | 36.45  | 30.39    | 13.79    | 2.78     | 0.17      | 0.94   | 1.12    | −0.03    | 2.96     |
| NRB-9     | 4.03  | 14.75 | 26.41  | 25.07    | 29.11    | 2.64     | 0.00      | 1.17   | 1.21    | −0.28    | 2.23     |
| NRB-10    | 2.17  | 1.74  | 17.90  | 55.52    | 21.27    | 1.06     | 0.02      | 1.46   | 0.84    | −0.87    | 5.13     |
| NRB-11    | 0.13  | 0.14  | 3.04   | 61.39    | 34.76    | 1.19     | 0.00      | 1.83   | 0.57    | −0.01    | 4.25     |
| NRB-12    | 1.00  | 1.87  | 44.96  | 47.46    | 4.94     | 0.11     | 0.00      | 1.04   | 0.67    | −0.27    | 4.14     |
| NRB-13    | 6.85  | 15.27 | 51.31  | 24.12    | 2.47     | 0.39     | 0.10      | 0.52   | 0.90    | −0.18    | 3.70     |
| NRB-14    | 34.81 | 51.73 | 12.03  | 1.51     | 0.15     | 0.00     | 0.00      | −0.69  | 0.71    | 0.65     | 3.52     |
| NRB-15    | 8.48  | 16.39 | 23.65  | 33.97    | 14.97    | 2.91     | 0.05      | 0.89   | 1.24    | −0.20    | 2.43     |
| NRB-16    | 4.42  | 13.29 | 30.83  | 27.42    | 18.55    | 2.95     | 0.04      | 1.03   | 1.17    | −0.10    | 2.54     |
| NRB-17    | 11.29 | 9.92  | 28.37  | 29.50    | 16.58    | 4.30     | 0.69      | 0.96   | 1.34    | −0.14    | 2.62     |
| NRB-18    | 0.22  | 1.23  | 6.58   | 30.36    | 54.83    | 5.96     | 0.45      | 2.09   | 0.79    | −0.76    | 4.60     |
| NRB-19    | 2.05  | 3.04  | 11.03  | 47.66    | 31.24    | 4.74     | 0.35      | 1.69   | 0.96    | −0.73    | 4.65     |
| NRB-20    | 13.17 | 12.47 | 44.08  | 27.30    | 2.61     | 0.37     | 0.00      | 0.45   | 1.03    | −0.40    | 2.77     |
| NRB-21    | 0.00  | 0.00  | 0.09   | 8.23     | 57.28    | 34.42    | 0.00      | 2.76   | 0.60    | −0.22    | 2.57     |
| NRB-22    | 0.01  | 0.07  | 0.68   | 5.97     | 83.13    | 9.94     | 0.20      | 2.52   | 0.48    | 0.05     | 1.23     |
| NRB-23    | 0.00  | 0.00  | 0.05   | 14.93    | 66.34    | 18.54    | 0.14      | 2.54   | 0.58    | 0.01     | 3.11     |
| NRB-24    | 0.00  | 0.00  | 0.38   | 26.98    | 64.50    | 7.87     | 0.29      | 2.31   | 0.58    | 0.01     | 3.32     |
| NRB-25    | 0.00  | 0.00  | 3.79   | 53.32    | 39.09    | 3.81     | 0.00      | 1.93   | 0.63    | 0.27     | 2.84     |
| NRB-26    | 0.94  | 0.66  | 0.13   | 3.52     | 65.85    | 28.90    | 0.00      | 2.69   | 0.71    | −2.37    | 15.30    |
| NRB-27    | 0.00  | 0.00  | 0.00   | 4.27     | 23.77    | 70.69    | 1.29      | 3.19   | 0.57    | −1.27    | 4.24     |
| NRB-28    | 2.69  | 0.00  | 1.53   | 7.91     | 65.76    | 22.12    | 0.00      | 2.50   | 0.89    | −2.44    | 11.95    |
| NRB-29    | 0.00  | 0.01  | 0.26   | 16.61    | 76.08    | 7.02     | 0.04      | 2.40   | 0.49    | −0.38    | 4.51     |
| NRB-30    | 0.00  | 0.87  | 1.86   | 4.64     | 80.16    | 12.37    | 0.09      | 2.52   | 0.57    | −1.71    | 11.40    |
| NRB-31    | 0.00  | 0.00  | 0.00   | 5.56     | 71.39    | 21.79    | 1.28      | 2.69   | 0.53    | 0.59     | 4.09     |
| NRB-32    | 0.00  | 0.00  | 0.00   | 4.86     | 69.75    | 25.38    | 0.00      | 2.70   | 0.51    | 0.26     | 3.04     |
| NRB-33    | 0.00  | 0.09  | 1.69   | 7.50     | 78.30    | 12.36    | 0.06      | 2.52   | 0.55    | 0.00     | 1.39     |
| NRB-34    | 0.00  | 0.82  | 0.84   | 19.45    | 70.07    | 8.81     | 0.00      | 2.35   | 0.61    | −1.04    | 6.64     |
| NRB-35    | 0.00  | 0.00  | 0.68   | 28.73    | 66.69    | 3.89     | 0.00      | 2.24   | 0.53    | −0.41    | 3.06     |
| NRB-36    | 0.00  | 0.00  | 0.43   | 36.80    | 60.09    | 2.69     | 0.00      | 2.15   | 0.54    | −0.19    | 2.32     |
| NRB-37    | 0.00  | 0.00  | 1.69   | 22.85    | 72.63    | 2.85     | 0.00      | 2.27   | 0.52    | −0.96    | 4.27     |
| NRB-38    | 0.02  | 0.20  | 1.37   | 17.04    | 56.20    | 24.91    | 0.26      | 2.59   | 0.77    | 0.01     | 1.19     |
| NRB-39    | 0.00  | 0.92  | 21.73  | 68.74    | 8.63     | 0.00     | 0.00      | 1.35   | 0.56    | −0.33    | 3.68     |
| NRB-40    | 0.00  | 0.00  | 0.59   | 7.41     | 75.36    | 16.63    | 0.00      | 2.58   | 0.51    | −0.15    | 5.01     |
| NRB-41    | 0.00  | 0.02  | 0.34   | 30.67    | 60.66    | 8.31     | 0.00      | 2.23   | 0.68    | −0.11    | 1.00     |
| NRB-42    | 0.00  | 0.00  | 1.58   | 10.28    | 80.15    | 8.01     | 0.00      | 2.45   | 0.49    | −0.93    | 6.91     |
| NRB-43    | 0.09  | 0.05  | 0.38   | 19.75    | 70.86    | 9.00     | 0.03      | 2.38   | 0.55    | −0.56    | 5.82     |
| NRB-44    | 0.00  | 0.00  | 0.07   | 1.27     | 78.58    | 14.66    | 0.13      | 2.64   | 0.39    | 1.23     | 5.69     |
| NRB-45    | 0.01  | 0.01  | 0.09   | 0.96     | 62.20    | 28.33    | 0.40      | 2.80   | 0.50    | 0.46     | 0.86     |
| NRB-46    | 0.00  | 0.64  | 19.02  | 45.10    | 33.00    | 3.01     | 0.00      | 1.69   | 0.79    | −0.06    | 2.51     |
| NRB-47    | 1.45  | 0.37  | 1.50   | 9.44     | 49.43    | 29.72    | 0.22      | 2.62   | 0.88    | −1.90    | 9.43     |
| NRB-48    | 0.03  | 0.25  | 6.56   | 61.62    | 30.01    | 1.28     | 0.00      | 1.76   | 0.61    | 0.06     | 3.55     |
| NRB-49    | 0.00  | 0.30  | 0.39   | 19.34    | 75.23    | 5.23     | 0.00      | 2.34   | 0.51    | −0.94    | 6.27     |
| NRB-50    | 0.00  | 0.00  | 16.58  | 18.43    | 58.33    | 4.18     | 0.00      | 2.01   | 0.82    | −0.74    | 2.51     |
| NRB-51    | 0.00  | 0.02  | 0.06   | 4.75     | 91.18    | 4.06     | 0.00      | 2.49   | 0.30    | −0.55    | 13.36    |
| NRB-52    | 0.00  | 0.00  | 0.01   | 2.88     | 82.80    | 2.64     | 0.01      | 2.50   | 0.25    | −0.17    | 16.44    |
| NRB-53    | 0.00  | 0.00  | 0.35   | 6.83     | 84.65    | 11.72    | 0.04      | 2.54   | 0.44    | −0.03    | 6.43     |
| NRB-54    | 0.00  | 0.07  | 0.80   | 3.16     | 91.50    | 5.18     | 0.00      | 2.50   | 0.35    | −1.53    | 18.36    |
| NRB-55    | 0.00  | 0.02  | 0.21   | 10.53    | 78.57    | 5.80     | 0.07      | 2.45   | 0.43    | −0.50    | 6.74     |
| NRB-56    | 0.00  | 0.30  | 86.90  | 11.84    | 1.11     | 0.02     | 0.00      | 0.64   | 0.39    | 2.54     | 9.88     |
| NRB-57    | 0.00  | 0.01  | 0.06   | 4.26     | 74.08    | 10.16    | 0.03      | 2.57   | 0.40    | 0.41     | 6.62     |
| NRB-58    | 0.42  | 0.54  | 2.30   | 46.87    | 5.71     | 58.83    | 0.00      | 2.53   | 1.05    | −0.47    | 2.18     |
| NRB-59    | 0.02  | 1.32  | 0.03   | 47.80    | 47.44    | 0.08     | 0.03      | 1.97   | 0.58    | −0.92    | 5.41     |

highlighting that a substantial fraction of the coast is morphologically immature despite its high-energy setting — an apparent paradox resolved by the distinction between energy and maturity developed below.

As expected from their complementary definitions, angularity and roundness show a strong inverse relationship (Pearson  $r \approx -0.83$ ; Fig. 5). Rather than an independent finding, this tight coupling is best read as an internal consistency check: it confirms that the automated, edge-scale Sobel index and the visual, grain-corner-scale Powers classification capture the same process — progressive mechanical abrasion during transport — at two different scales of observation. Low-angularity samples correspond to high roundness classes (mature, far-

travelled grains), whereas high-angularity samples correspond to low roundness (immature, proximal grains).

Spatially, a clear gradient emerges along the study area. Northern sectors (La Guajira and northern Magdalena) are characterized by lower angularity and higher roundness, reflecting high-energy conditions and sustained sediment reworking (Fig. 5). Central sectors (Atlántico) display the greatest variability, including both highly angular and moderately rounded sediments, indicating transitional conditions and mixed sediment sources (Fig. 5). Southern sectors (Bolívar, Sucre, Córdoba, and Antioquia) are dominated by subangular to angular grains, suggesting shorter transport pathways, reduced reworking, and stronger influence of local sediment inputs (Fig. 5).



**Fig. 3.** Spatial variation of granulometric parameters (median grain size, sorting, skewness, and kurtosis) from north to south. The figure presents the existing regional trends and variability in sediment texture and depositional conditions.

Overall, grain morphology indicates that shape is controlled jointly by transport distance, hydrodynamic energy, and sediment source. Because the angularity-roundness signal is both strong and largely independent of grain size, it provides the most robust morphological discriminant in the multi-proxy framework and a key axis (PC3) in the multivariate structure.

#### 4.2. Depositional environments, proxy coupling, and sediment provenance

Sahu's discriminant functions (Y1, Y2, Y3) provide a first-order classification of depositional environments and identify localized deviations (Fig. 6). Interpreted together with the other proxies, they confirm a dominant beach and shallow-agitated-marine system with a subordinate fluvial signature.

The Y1 function classifies the great majority of samples as beach deposits (54 of 59; ~91.5%), with only five sites falling in the aeolian field (Fig. 6). These aeolian-classified samples coincide with well-sorted, fine backshore sands in sectors where dune reworking is documented (Rangel-Buitrago et al., 2023), consistent with secondary aeolian processing of beach sand.

The Y2 function is uniform: all samples exceed the 65.365 threshold (values from ~78 to ~359), placing the entire dataset within shallow-agitated-marine conditions. This uniformity reflects the pervasive, high-energy wave climate of the coast and indicates that, at the regional scale, depositional energy is consistently high even where maturity is not.

The Y3 function refines the interpretation by separating marine from fluvial influence. Most samples (~78%) classify as shallow marine, confirming the dominance of coastal processes, while a subset (~22%) records fluvial influence (Fig. 6). The fluvial signature is concentrated in the north, where the Magdalena and Ranchería systems and SNSM drainage deliver continental material, and is weakest in the south-central sectors dominated by reworked marine sand. This northern fluvial signature is consistent with the independent proxies: the same sectors combine gravel and very coarse sand enrichment with poorer sorting (Section 4.1), higher angularity and lower roundness where supply is proximal, and locally anomalous optical signatures (e.g., NRB-26), so that the fluvial influence inferred from Y3 is corroborated by texture, morphology, and color rather than resting on grain-size statistics alone.

Northern sectors (La Guajira and Magdalena) therefore show the greatest depositional diversity, combining beach, fluvial, and aeolian signatures and reflecting the convergence of multiple sources with dynamic forcing. Central and southern sectors are more homogeneous, dominated by reworked shallow-marine sand.

These results also expose a fundamental limitation of discriminant schemes. Sahu's functions, being based solely on grain-size statistics, force continuous variability into discrete categories and cannot resolve post-depositional reworking, mixing, or transport history. Our multi-proxy data show that several samples assigned to the same Sahu class differ markedly in color and morphology, demonstrating that grain size alone underdetermines environment. This discrepancy is not a flaw in

**Table 4**

CIELAB colorimetric parameters (L, a\*, b\*), Angularity, Powers numeric roundness of surface sediments collected from 59 beach sites along the Caribbean coast Colombia.

| Sample ID | L*    | a*    | b*    | Chroma (C*) | Hue angle (h°) | COLOR                        | CLUSTER | Angularity (mean Sobel edge intensity) | Powers numeric roundness (1–6) | Powells description |
|-----------|-------|-------|-------|-------------|----------------|------------------------------|---------|----------------------------------------|--------------------------------|---------------------|
| NRB-1     | 57.43 | 0.35  | 19.68 | 19.62       | 89.00          | Very Bright/Highly Saturated | C1      | 0.030                                  | 5                              | Rounded             |
| NRB-2     | 61.80 | −1.06 | 25.32 | 25.35       | 92.40          | Very Bright/Highly Saturated | C1      | 0.040                                  | 5                              | Rounded             |
| NRB-3     | 60.64 | −0.02 | 9.66  | 9.66        | 90.10          | Bright/Moderately Saturated  | C2      | 0.036                                  | 5                              | Rounded             |
| NRB-4     | 62.20 | −0.99 | 9.91  | 9.96        | 95.70          | Bright/Moderately Saturated  | C2      | 0.032                                  | 5                              | Rounded             |
| NRB-5     | 64.50 | −1.61 | 15.18 | 15.26       | 96.05          | Very Bright/Highly Saturated | C1      | 0.042                                  | 4                              | Subrounded          |
| NRB-6     | 65.88 | −1.52 | 10.05 | 10.16       | 98.61          | Bright/Moderately Saturated  | C2      | 0.039                                  | 5                              | Rounded             |
| NRB-7     | 65.29 | −1.20 | 10.57 | 10.63       | 96.45          | Bright/Moderately Saturated  | C2      | 0.037                                  | 5                              | Rounded             |
| NRB-8     | 62.36 | −0.69 | 7.37  | 7.40        | 95.38          | Intermediate (Transitional)  | C3      | 0.033                                  | 5                              | Rounded             |
| NRB-9     | 60.23 | −1.58 | 14.92 | 15.01       | 96.06          | Bright/Moderately Saturated  | C2      | 0.032                                  | 5                              | Rounded             |
| NRB-10    | 58.50 | −1.29 | 9.98  | 10.06       | 97.36          | Intermediate (Transitional)  | C3      | 0.039                                  | 5                              | Rounded             |
| NRB-11    | 54.65 | −1.68 | 7.24  | 7.43        | 103.05         | Anomalous/Special            | C5      | 0.056                                  | 4                              | Subrounded          |
| NRB-12    | 56.87 | −1.48 | 9.60  | 9.71        | 98.78          | Intermediate (Transitional)  | C3      | 0.043                                  | 4                              | Subrounded          |
| NRB-13    | 58.95 | −1.10 | 8.90  | 8.96        | 97.05          | Intermediate (Transitional)  | C3      | 0.037                                  | 5                              | Rounded             |
| NRB-14    | 55.29 | −1.33 | 11.92 | 11.99       | 96.39          | Intermediate (Transitional)  | C3      | 0.028                                  | 5                              | Rounded             |
| NRB-15    | 55.92 | −1.42 | 6.84  | 6.99        | 101.77         | Dark/Low Saturation          | C4      | 0.047                                  | 4                              | Subrounded          |
| NRB-16    | 59.90 | −1.58 | 6.00  | 6.21        | 104.76         | Dark/Low Saturation          | C4      | 0.046                                  | 4                              | Subrounded          |
| NRB-17    | 53.30 | −1.77 | 5.92  | 6.18        | 106.64         | Dark/Low Saturation          | C4      | 0.062                                  | 3                              | Subangular          |
| NRB-18    | 55.54 | −1.11 | 3.67  | 3.84        | 106.87         | Dark/Low Saturation          | C4      | 0.059                                  | 4                              | Subrounded          |
| NRB-19    | 53.95 | −1.71 | 6.55  | 6.77        | 104.62         | Intermediate (Transitional)  | C3      | 0.055                                  | 4                              | Subrounded          |
| NRB-20    | 60.51 | −1.40 | 10.81 | 10.90       | 97.40          | Bright/Moderately Saturated  | C2      | 0.036                                  | 4                              | Subrounded          |
| NRB-21    | 55.68 | −1.91 | 9.53  | 9.72        | 101.34         | Intermediate (Transitional)  | C3      | 0.075                                  | 2                              | Angular             |
| NRB-22    | 49.77 | −3.03 | 8.62  | 9.14        | 109.37         | Intermediate (Transitional)  | C3      | 0.081                                  | 2                              | Angular             |
| NRB-23    | 56.84 | −1.82 | 11.04 | 11.19       | 99.70          | Intermediate (Transitional)  | C3      | 0.067                                  | 2                              | Angular             |
| NRB-24    | 55.06 | −1.41 | 9.24  | 9.35        | 98.65          | Intermediate (Transitional)  | C3      | 0.060                                  | 3                              | Subangular          |
| NRB-25    | 54.32 | −1.96 | 8.71  | 8.93        | 102.67         | Intermediate (Transitional)  | C3      | 0.064                                  | 3                              | Subangular          |
| NRB-26    | 41.82 | 1.22  | −0.65 | 1.38        | 331.95         | Anomalous/Special            | C5      | 0.109                                  | 2                              | Angular             |
| NRB-27    | 49.26 | 0.91  | 3.14  | 3.27        | 73.86          | Anomalous/Special            | C5      | 0.095                                  | 3                              | Subangular          |
| NRB-28    | 52.97 | −1.02 | 8.55  | 8.61        | 96.82          | Intermediate (Transitional)  | C3      | 0.057                                  | 4                              | Subrounded          |
| NRB-29    | 58.91 | −2.09 | 12.46 | 12.63       | 99.52          | Bright/Moderately Saturated  | C2      | 0.064                                  | 3                              | Subangular          |
| NRB-30    | 55.34 | −1.62 | 9.55  | 9.69        | 99.64          | Intermediate (Transitional)  | C3      | 0.045                                  | 4                              | Subrounded          |
| NRB-31    | 56.14 | −1.53 | 10.74 | 10.85       | 98.11          | Intermediate (Transitional)  | C3      | 0.043                                  | 4                              | Subrounded          |
| NRB-32    | 57.65 | −1.23 | 9.66  | 9.73        | 97.26          | Intermediate (Transitional)  | C3      | 0.061                                  | 2                              | Angular             |
| NRB-33    | 55.70 | −1.27 | 9.58  | 9.66        | 97.55          | Intermediate (Transitional)  | C3      | 0.065                                  | 2                              | Angular             |
| NRB-34    | 59.50 | −1.59 | 12.12 | 12.22       | 97.48          | Bright/Moderately Saturated  | C2      | 0.055                                  | 3                              | Subangular          |
| NRB-35    | 59.61 | −2.41 | 12.90 | 13.12       | 100.58         | Bright/Moderately Saturated  | C2      | 0.056                                  | 3                              | Subangular          |
| NRB-36    | 59.10 | −1.95 | 10.86 | 11.04       | 100.18         | Bright/Moderately Saturated  | C2      | 0.060                                  | 3                              | Subangular          |
| NRB-37    | 60.51 | −1.52 | 11.32 | 11.42       | 97.64          | Bright/Moderately Saturated  | C2      | 0.051                                  | 3                              | Subangular          |
| NRB-38    | 58.73 | −0.92 | 8.74  | 8.78        | 95.99          | Intermediate (Transitional)  | C3      | 0.059                                  | 3                              | Subangular          |
| NRB-39    | 60.56 | −1.68 | 13.94 | 14.04       | 96.86          | Very Bright/Highly Saturated | C1      | 0.038                                  | 4                              | Subrounded          |

(continued on next page)



Table 4 (continued)

| Sample ID | L*    | a*    | b*    | Chroma (C*) | Hue angle (h°) | COLOR                        | CLUSTER | Angularity (mean Sobel edge intensity) | Powers numeric roundness (1–6) | Powells description |
|-----------|-------|-------|-------|-------------|----------------|------------------------------|---------|----------------------------------------|--------------------------------|---------------------|
| NRB-40    | 60.31 | −1.99 | 11.11 | 11.29       | 100.14         | Bright/Moderately Saturated  | C2      | 0.052                                  | 3                              | Subangular          |
| NRB-41    | 60.10 | −1.98 | 10.74 | 10.92       | 100.44         | Bright/Moderately Saturated  | C2      | 0.059                                  | 3                              | Subangular          |
| NRB-42    | 56.23 | −1.90 | 13.35 | 13.48       | 98.11          | Intermediate (Transitional)  | C3      | 0.066                                  | 2                              | Angular             |
| NRB-43    | 58.24 | −2.03 | 10.06 | 10.26       | 101.39         | Intermediate (Transitional)  | C3      | 0.064                                  | 2                              | Angular             |
| NRB-44    | 54.36 | −2.09 | 8.71  | 8.96        | 103.48         | Intermediate (Transitional)  | C3      | 0.071                                  | 2                              | Angular             |
| NRB-45    | 54.79 | −0.93 | 7.79  | 7.85        | 96.77          | Intermediate (Transitional)  | C3      | 0.069                                  | 2                              | Angular             |
| NRB-46    | 68.53 | −1.95 | 12.99 | 13.13       | 98.53          | Intermediate (Transitional)  | C3      | 0.027                                  | 5                              | Rounded             |
| NRB-47    | 53.79 | −1.19 | 7.45  | 7.54        | 99.11          | Intermediate (Transitional)  | C3      | 0.061                                  | 2                              | Angular             |
| NRB-48    | 64.02 | −2.03 | 16.21 | 16.33       | 97.14          | Very Bright/Highly Saturated | C1      | 0.046                                  | 3                              | Subangular          |
| NRB-49    | 55.08 | −1.77 | 10.92 | 11.07       | 99.22          | Intermediate (Transitional)  | C3      | 0.069                                  | 2                              | Angular             |
| NRB-50    | 55.08 | −1.77 | 10.92 | 11.07       | 99.22          | Intermediate (Transitional)  | C3      | 0.069                                  | 2                              | Angular             |
| NRB-51    | 55.41 | −2.60 | 9.01  | 9.38        | 106.12         | Intermediate (Transitional)  | C3      | 0.065                                  | 2                              | Angular             |
| NRB-52    | 56.09 | −2.82 | 9.58  | 9.99        | 106.38         | Intermediate (Transitional)  | C3      | 0.069                                  | 2                              | Angular             |
| NRB-53    | 55.74 | −2.77 | 9.39  | 9.79        | 106.47         | Intermediate (Transitional)  | C3      | 0.067                                  | 2                              | Angular             |
| NRB-54    | 54.13 | −1.80 | 7.95  | 8.15        | 102.76         | Intermediate (Transitional)  | C3      | 0.072                                  | 2                              | Angular             |
| NRB-55    | 57.38 | −0.82 | 11.15 | 11.18       | 94.19          | Intermediate (Transitional)  | C3      | 0.060                                  | 2                              | Angular             |
| NRB-56    | 58.30 | −1.28 | 12.07 | 12.14       | 96.07          | Intermediate (Transitional)  | C3      | 0.060                                  | 3                              | Subangular          |
| NRB-57    | 59.42 | −1.86 | 10.92 | 11.08       | 99.65          | Intermediate (Transitional)  | C3      | 0.060                                  | 3                              | Subangular          |
| NRB-58    | 59.75 | −2.08 | 11.92 | 12.10       | 99.89          | Intermediate (Transitional)  | C3      | 0.053                                  | 3                              | Subangular          |
| NRB-59    | 52.04 | −1.29 | 11.45 | 11.52       | 96.41          | Intermediate (Transitional)  | C3      | 0.042                                  | 4                              | Subrounded          |

the data but evidence for the continuum structure we develop below.

Integrating texture, color, and morphology reveals a coherent system in which the proxies respond, with differing sensitivity, to a common hydrodynamic control (Fig. 7). Importantly, the strength of coupling depends on whether proxies share an underlying mechanism, and we interpret each relationship on its own terms rather than assuming uniformly strong correlations.

Lightness (L\*) increases weakly with sorting ( $r \approx 0.28$ ; Fig. 7A). The relationship is modest but directionally consistent: better-sorted sediments, produced by sustained wave grading in exposed sectors, tend to be brighter and more optically mature. The weakness of the correlation reflects the fact that L\* also responds to composition and surface coatings (moisture, another general control on L\*, was standardized by air-drying prior to measurement), so that sorting explains only part of its variance, precisely the partial independence that makes color a useful complementary proxy.

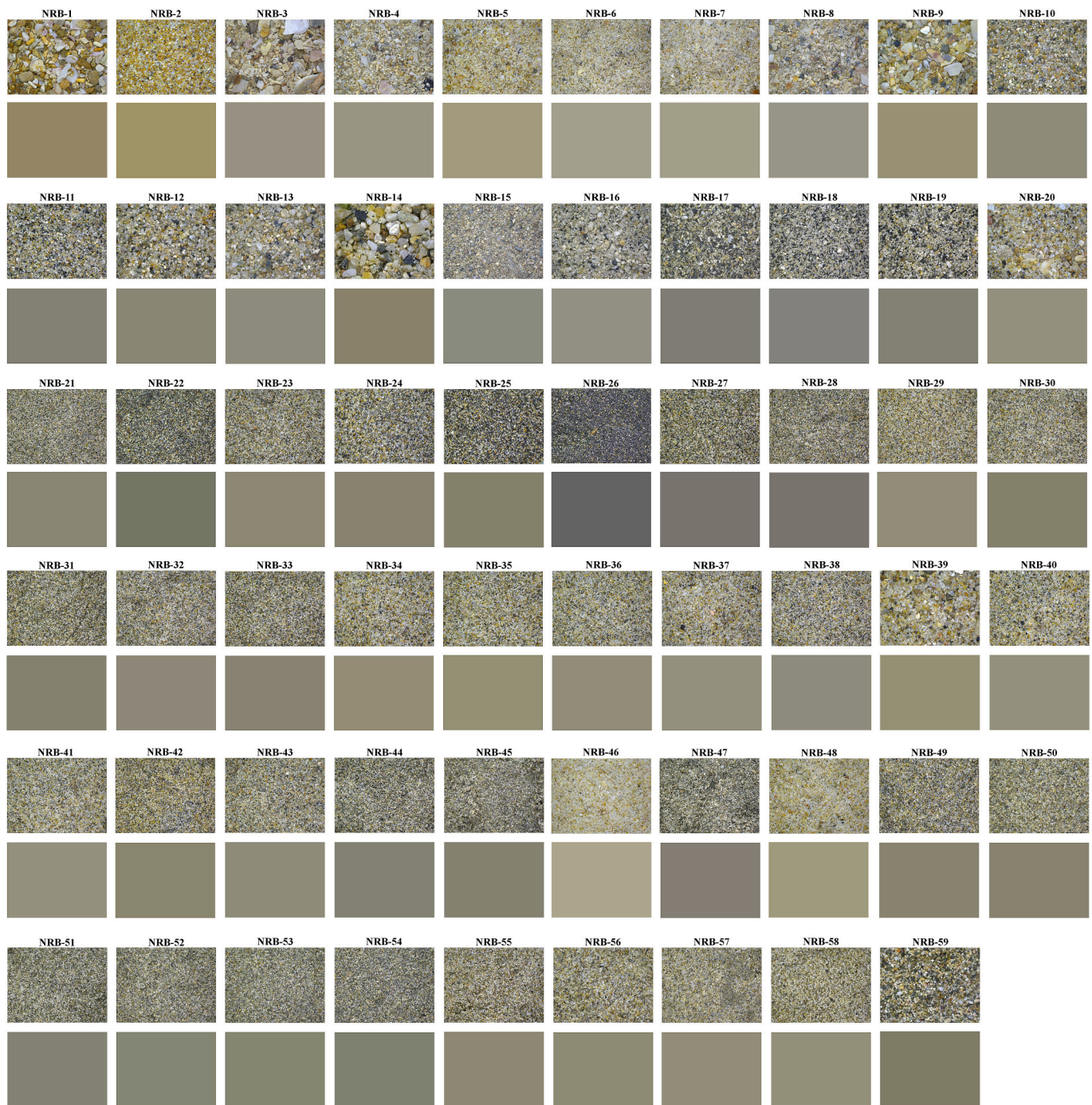
Chroma (C\*) decreases weakly with median grain size in  $\phi$  units ( $r \approx -0.24$ ; Fig. 7B); because higher  $\phi$  denotes finer sediment, this means that more saturated colors tend to occur in coarser, more reworked sands, particularly in the northern exposed sectors. As with L\*, the modest magnitude indicates that saturation is governed by oxidation and mineral coating as much as by grain size, again confirming that color adds information beyond texture. Part of this weak grain-size dependence may also be physical–optical rather than compositional: as grain size increases, surface roughness at the image scale increases, and intergranular micro-shadows and multiple scattering can modify apparent chroma and lightness independently of mineralogy. Because

all samples were imaged dry, under identical illumination geometry and camera distance, these effects operate similarly across the dataset; they nevertheless represent an intrinsic limitation of image-based colorimetry that should be kept in mind when comparing sediments of very different grain size.

Morphology shows the strongest internal coupling. Angularity increases with transport intensity (Sahu Y2;  $r \approx 0.29$ ; Fig. 7C) and, far more strongly and as expected by definition, is inversely related to roundness ( $r \approx -0.83$ ; Section 4.1). The contrast between the strong within-morphology coupling and the weaker cross-domain optical–textural couplings is itself a central result: it shows that the proxies are not redundant. Each captures a partly independent dimension of the sedimentary system, which is exactly why their integration constrains process more tightly than any single descriptor.

Synthesizing these relationships, the data defines a unified system in which hydrodynamic energy is the primary control, shaping grain size, sorting, color, and morphology simultaneously but through distinct mechanisms. High-energy environments generate coarse-skewed, well-sorted, bright, saturated, and rounded sediments, whereas lower-energy or proximally supplied environments produce finer-skewed, less sorted, darker, and more angular material. The coupling is therefore best described as coherent and process-consistent rather than uniformly strong, a distinction that matters for how the system should be modeled and managed.

The sedimentary characteristics of the 59 analyzed coastal sites reflect a complex provenance system controlled by the interaction of major fluvial inputs, coastal processes, and regional geology. The



**Fig. 4.** Representative sediment samples and corresponding color patches for each site. The figure illustrates variations in sediment texture and color, supporting the interpretation of compositional differences and optical properties.

Colombian Caribbean margin is supplied by a series of large drainage systems originating in the Andean cordilleras, including the Magdalena-Cauca, Sinú, Atrato, Ranchería, and Sierra Nevada de Santa Marta (SNSM) rivers, which collectively deliver substantial volumes of terrigenous material to the coastal zone (Restrepo López et al., 2017; Betancurth and Cañón, 2025; Ramírez et al., 2025). These rivers drain diverse lithological provinces, including metamorphic, igneous, sedimentary, and volcanic rocks, resulting in a heterogeneous sediment supply that is subsequently reworked along the coastline (Correa and Morton, 2010). This diversity is reflected in the dataset, where sites such as NRB-1 (Yokuyokutshi) and NRB-14 (Los Ángeles) exhibit coarse, poorly sorted sediments with significant gravel content, indicating

direct lithic-fragment input from nearby sources.

Among these sources, the Magdalena River system plays a dominant role at the regional scale, historically delivering on the order of ~140–170 million tons of sediment annually to the Caribbean Sea (Restrepo et al., 2015; Restrepo and Escobar, 2018). However, its influence on present-day beaches is strongly modified by anthropogenic interventions, particularly the construction of jetties at Bocas de Ceniza. These structures have redirected a large proportion of sediment offshore toward the Magdalena submarine fan, reducing the supply of fine to medium sands to adjacent coastal sectors (Martínez et al., 1990; Higgins et al., 2015; Ercilla et al., 2002a, 2002b). This is clearly reflected in Atlántico Department sites, where sediments are predominantly fine,



**Table 5**  
Colorimetric classification of sediments based on CIELab-derived optical properties.

| Cluster                           | Criteria                                   | Interpretation                           |
|-----------------------------------|--------------------------------------------|------------------------------------------|
| C1 – Very bright/Highly saturated | $L^* \geq 62$ AND $C^* \geq 14$            | Highly mature, oxidized, quartz-rich.    |
| C2 – Bright/Moderately saturated  | $L^* 58\text{--}62$ AND $C^* \geq 10$      | Mature, well reworked.                   |
| C3 – Intermediate (Transitional)  | $L^* 52\text{--}58$ AND $C^* 7\text{--}12$ | Transitional maturity.                   |
| C4 – Dark/Low saturation          | $L^* < 52$ AND $C^* < 7$                   | Low textural maturity/organic influence. |
| C5 – Anomalous/Special            | $C^* < 4$ OR extreme $h^*$                 | Atypical sediment conditions.            |

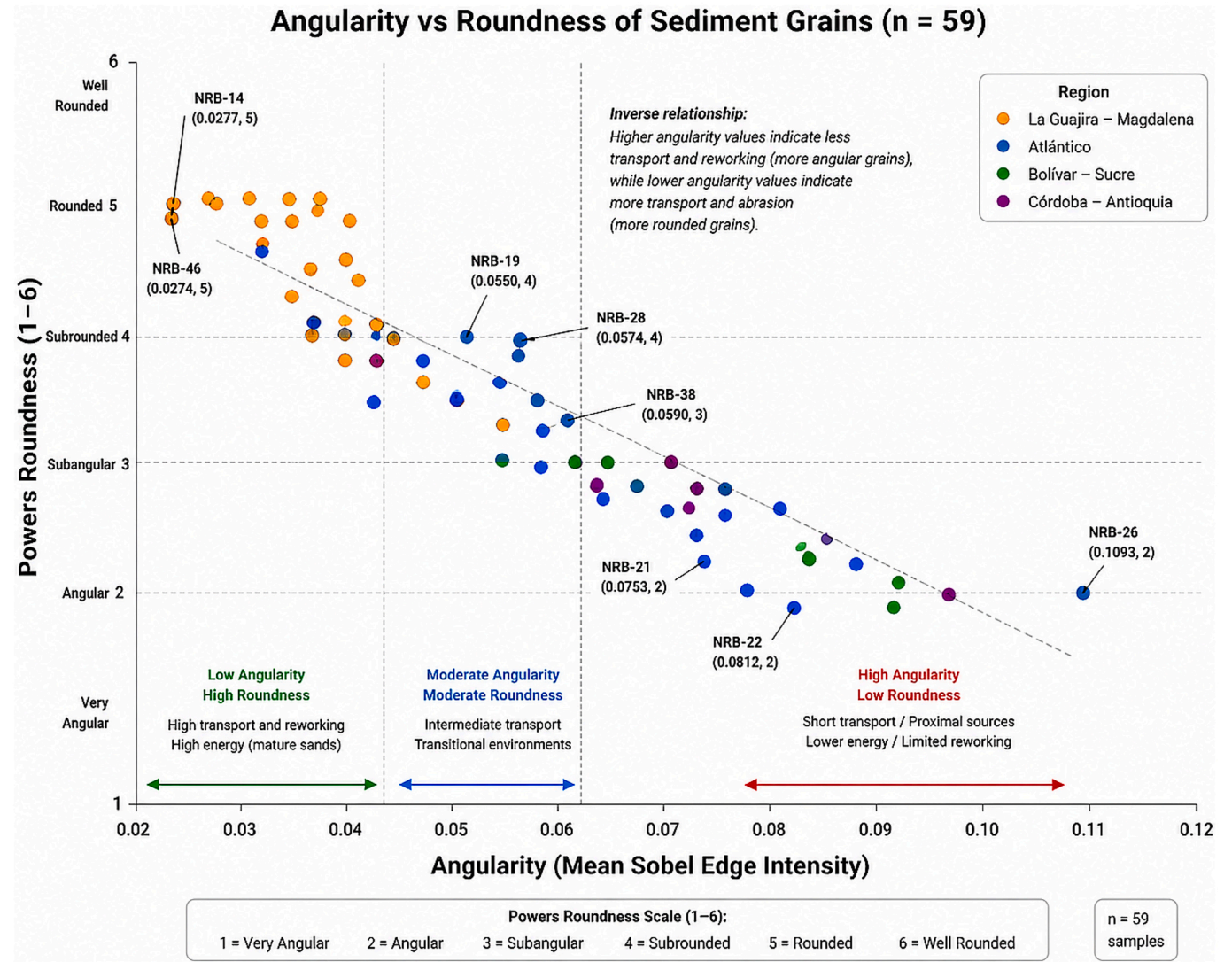
well sorted, and morphologically mature (e.g., NRB-23 Puerto Colombia, NRB-30 Caño Dulce, NRB-32 Palmarito), indicating strong reworking under limited sediment input conditions.

The spatial distribution of the samples reveals four main provenance domains. In the eastern sector (La Guajira and SNSM), sediments such as those at NRB-2 (Pilón de Azúcar) and NRB-6 (El Pájaro) are relatively coarse, well sorted, and optically bright, reflecting derivation from metamorphic and granitic sources and prolonged coastal reworking. In

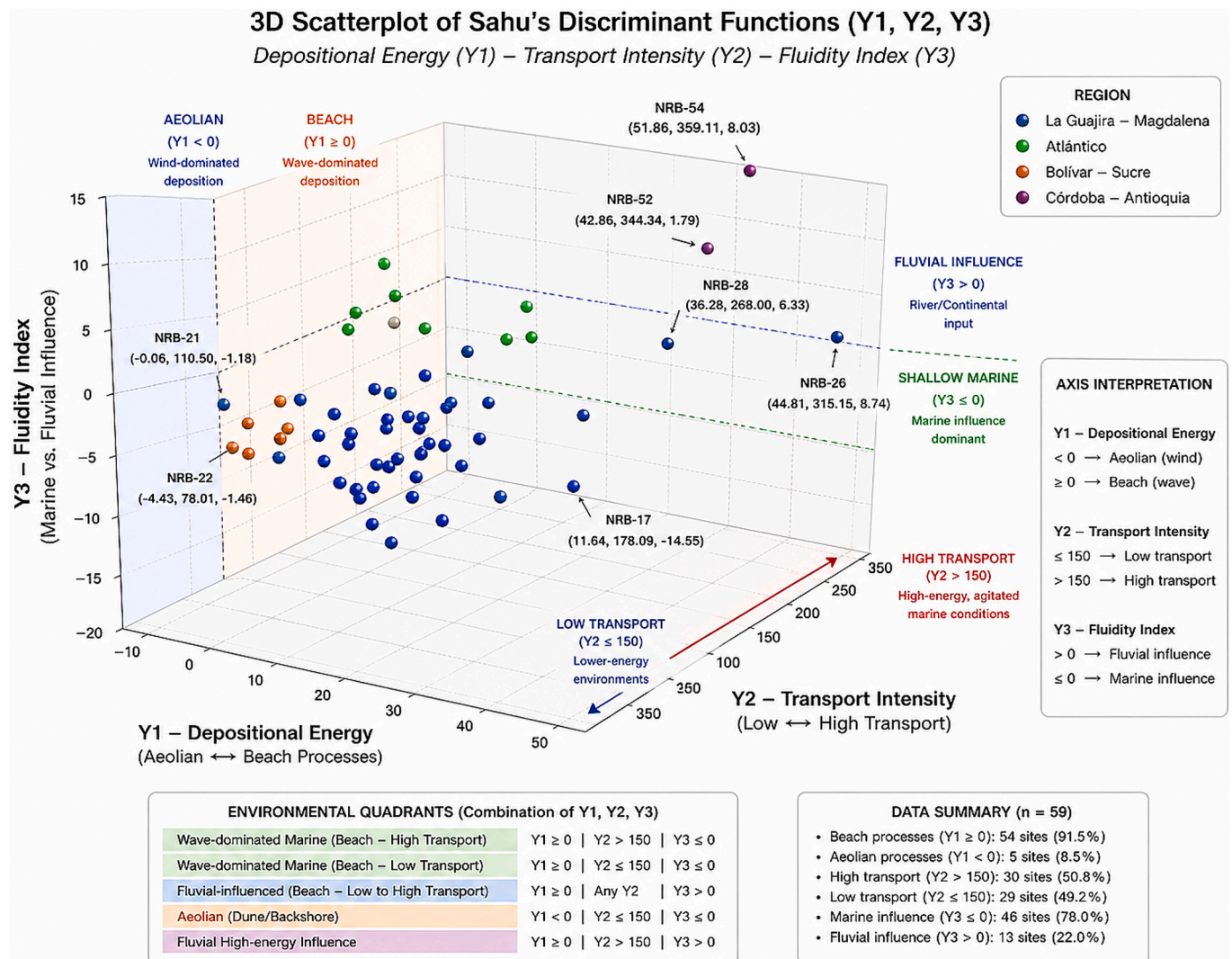
the central sector (Magdalena–Atlántico), sites such as NRB-20 (Punta Roca) and NRB-21 (Salgar) display mixed characteristics, including gravel enrichment and higher angularity, indicating contributions from both reworked sediments and local lithic inputs. In the western sector (Sucre–Córdoba–Antioquia), samples such as NRB-51 (San Bernardo del Viento) and NRB-54 (Puerto Escondido) are dominated by fine sands but exhibit higher angularity and lower roundness, suggesting shorter transport distances and a stronger influence of local fluvial sources, particularly from the Sinú and Atrato systems.

In addition to fluvial inputs, aeolian processes represent an important secondary sediment source, particularly in the Atlántico region (Rangel-Buitrago et al., 2023). Coastal dune systems contribute well-sorted quartz sands to the backshore and beach environments, as observed in sites such as NRB-22 (Pradomar Resort) and NRB-33 (Playa Linda), where fine, well sorted sediments and aeolian signatures are evident. Localized inputs from coastal cliff erosion further modify sediment composition in specific sites, notably NRB-20 (Punta Roca), where elevated gravel content and poor sorting indicate lithic-fragment contributions associated with headland erosion and high-energy wave impact (Gracia et al., 2024).

The provenance of the analyzed sediments is not controlled by a single source but results from the interaction of multiple sediment supply systems, subsequently modified by coastal hydrodynamics. The



**Fig. 5.** Relationship between grain angularity and roundness across all samples. The inverse trend reflects increasing transport distance and abrasion, distinguishing high-energy mature sediments from proximal, source-dominated materials.



**Fig. 6.** 3D scatterplot of Sahu's discriminant functions (Y1, Y2, Y3) showing depositional environments. The figure differentiates between aeolian, beach, shallow marine, and fluvial influences based on energy, transport intensity, and fluidity conditions.

coexistence of mature, well-reworked sands (e.g., NRB-2, NRB-46) and immature, source-influenced sediments (e.g., NRB-21, NRB-26) reflects a dynamic source-to-sink system in which sediment supply, transport pathways, and energy conditions interact continuously.

#### 4.3. Multivariate structure and the energy-maturity control

Principal Component Analysis shows that sediment variability is organized into a well-defined hierarchical structure in which statistical gradients map directly onto physical processes (Fig. 8). Three components capture the bulk of the variance and admit clear process interpretations.

The first component (PC1; ~43% of variance) is the dominant gradient and is interpreted as an energy-maturity axis. It loads positively on median grain size,  $L^*$ ,  $C^*$ , and roundness and negatively on angularity, ordering samples from mature, high-energy sediments (bright, saturated, rounded, coarser) to immature, lower-energy or proximal sediments (darker, weakly saturated, angular). That a single axis explains nearly half the variance is the central quantitative result of the study: it confirms that one dominant control structures the system.

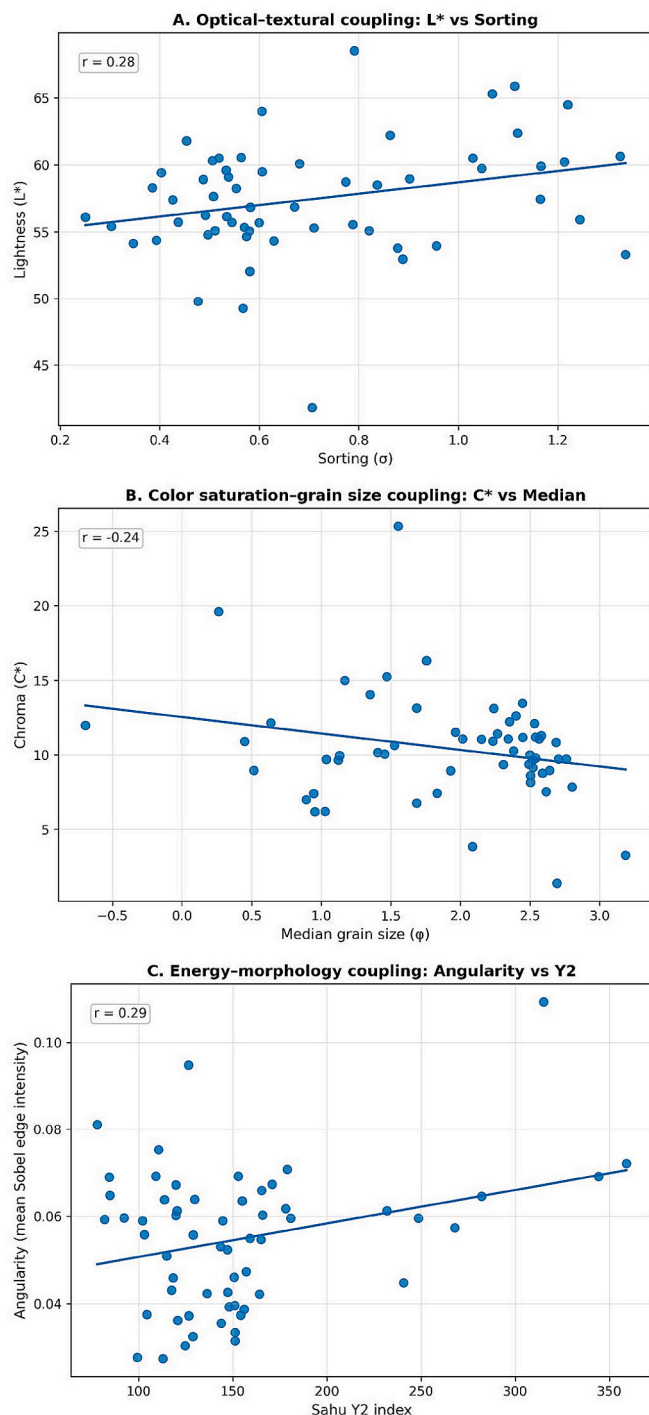
The second component (PC2; ~23% of variance) captures depositional variability, driven primarily by skewness and the Sahu indices (Y1 and Y3). It separates samples by depositional medium and asymmetry,

distinguishing fluvially and aeolially influenced sediments from strongly marine-reworked ones, and therefore encodes source and transport pathways rather than energy per se.

The third component (PC3; ~13% of variance) reflects morphological control, dominated by angularity and roundness. It isolates transport history and mechanical abrasion independently of color and grain size, confirming that morphology carries information not reducible to the other proxies and justifying its inclusion in the framework.

Hierarchical clustering (Ward's method) groups the 59 samples into four clusters reflecting integrated texture, color, morphology, and depositional signature (Fig. 9). Partitioned at the optimal level, Cluster 1 comprises 23 samples (e.g., NRB-1 to NRB-10, NRB-12–20, NRB-46, NRB-48, NRB-56, NRB-59) characterized by high  $L^*$ , moderate-to-high  $C^*$ , low angularity, and rounded grains — mature, high-energy, wave-dominated sediments. Cluster 2, the largest (29 samples; e.g., NRB-11, NRB-21–25, NRB-27, NRB-29, NRB-31–45, NRB-49–50, NRB-53, NRB-55, NRB-57–58), shows intermediate optical properties ( $L^* \approx 52$ –60), moderate chroma, and higher angularity — transitional, moderate-energy sediments. Cluster 3 (6 samples: NRB-28, NRB-30, NRB-47, NRB-51, NRB-52, NRB-54) is defined by high Y2, elevated angularity, and predominantly angular grains (Powers  $\approx 2$ ), recording strong hydrodynamic forcing but limited sediment equilibration, high-energy yet immature material. Cluster 4 is a single, strongly isolated sample (NRB-





**Fig. 7.** Coupling relationships between sediment properties: (A) lightness ( $L^*$ ) vs sorting, (B) chroma ( $C^*$ ) vs median grain size, and (C) angularity vs transport intensity (Y2). These plots demonstrate the integrated response of sediment characteristics to hydrodynamic forcing.

26) with the highest angularity (0.109), very low chroma ( $C^* \approx 1.38$ ), and anomalous hue ( $h^\circ \approx 332^\circ$ ), representing an extreme proximal, source-dominated end-member. The clustering thus recovers the same energy-maturity ordering as PCA while sharpening the end-members.

The results converge on a single organizing principle: sediment variability along the Colombian Caribbean coast is governed by a dominant, hierarchical control in which hydrodynamic energy regulates sediment maturity. This energy-maturity relationship provides a unifying framework linking texture, color, and morphology and accounts

for the dominance of PC1.

At the most basic level, grain size and sorting record the intensity and persistence of wave action (Dean and Dalrymple, 2004). High-energy environments selectively remove fines and concentrate coarser fractions, producing coarse-skewed, well-sorted sediments, whereas lower-energy or proximal settings retain finer, less-sorted material. This granulometric response is the foundation on which optical and morphological signals are built.

Optical maturity tracks this granulometric control. Sustained high energy removes surface coatings and fines and promotes oxidation of stable mineral surfaces, raising  $L^*$  and  $C^*$  (Spielvogel et al., 2004; Azzali et al., 2011).

Morphology supports this relationship. Repeated collisions in high-energy environments progressively abrade grains, lowering angularity and raising roundness (Kelly, 1983; Bray et al., 2024). The strong angularity-roundness coupling ( $r \approx -0.83$ ) demonstrates that this abrasion operates coherently across the region, while the persistence of angular grains in some high-energy sectors shows that energy and maturity, though linked, are not identical, immature material can be present where supply is proximal or transport recent.

Considered together, these variables define a hierarchically organized system in which energy is the primary driver, but sediment supply and transport history modulates the maturity achieved. High-energy, well-supplied, far-travelled sediments (e.g., NRB-2) reach the mature end-member, while high-energy but proximally supplied sediments (e.g., Cluster 3) remain immature.

#### 4.4. Optical and morphological proxies as process indicators

A principal contribution of this study is the demonstration that CIELAB parameters, especially  $L^*$  and  $C^*$ , function as robust, quantitative proxies for sediment maturity and environmental energy. Because they are cheap, rapid, and reproducible, they offer a practical complement to grain-size analysis for both research and monitoring.

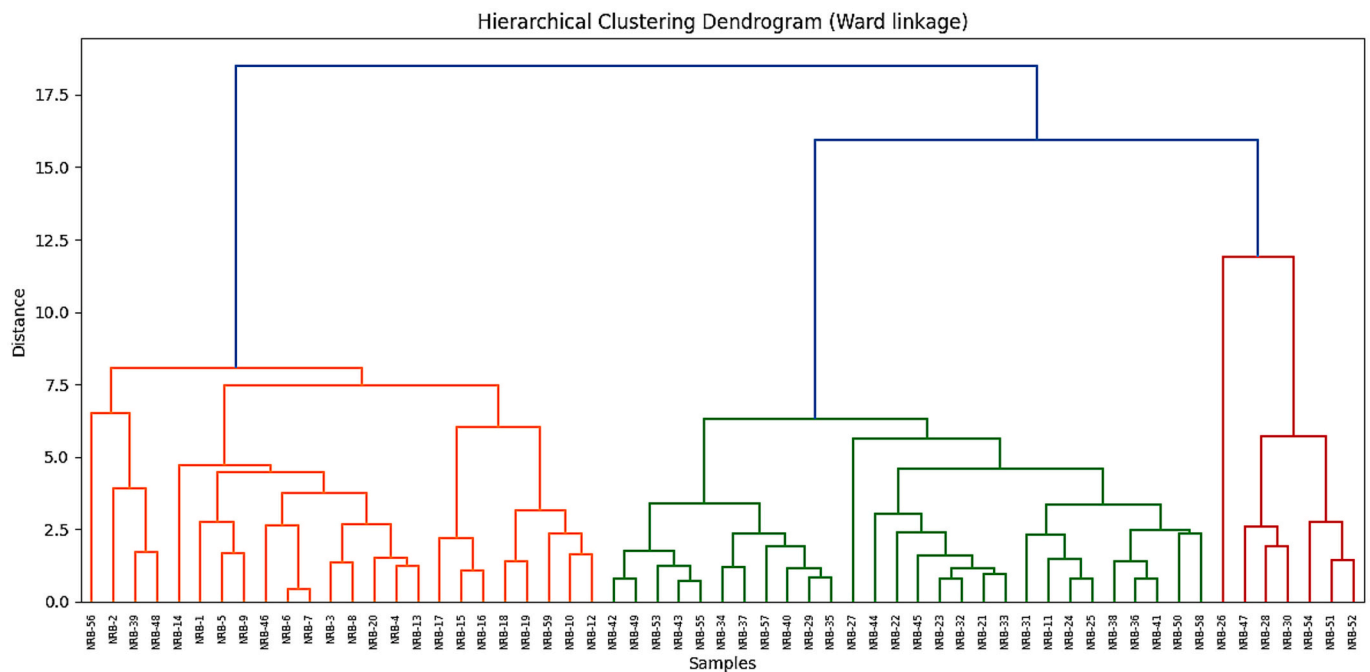
Lightness ( $L^*$ ) tracks maturity and reworking intensity. Higher  $L^*$  corresponds to brighter, well-washed, quartz-rich sands subjected to prolonged wave action (Pranzini et al., 2010), whereas lower  $L^*$  reflects darker, less reworked, or organic-influenced material. The continuous  $L^*$  range observed here (41.8–68.5) provides a fine-grained maturity scale that grain size alone cannot supply.

Chroma ( $C^*$ ) adds complementary information by quantifying saturation, which is closely tied to oxidation and mineral composition (Azzali et al., 2011). High  $C^*$  (e.g., NRB-2,  $C^* \approx 25.4$ ; NRB-1,  $C^* \approx 19.6$ ) marks yellow, iron-oxide-coated, oxidized sands typical of mature high-energy settings, while very low  $C^*$  (e.g., NRB-26,  $C^* \approx 1.38$ ) marks anomalous, lithic- or heavy-mineral-rich material with minimal oxidation.

The joint behavior of  $L^*$  and  $C^*$  couples coherently, if modestly, with texture and morphology (Asensio-Montesinos et al., 2020): high- $L^*$ -high- $C^*$  sediments tend to be coarser, better sorted, and rounded, whereas low- $L^*$ -low- $C^*$  sediments tend to be finer, less sorted, and angular. The modest correlation coefficients (Section 4.2) do not weaken this conclusion; rather, they show that color resolves maturity contrasts that texture leaves ambiguous, which is the practical justification for adding colorimetry to the toolkit.

These findings are consistent with prior work establishing colorimetry as a sediment indicator (Pranzini et al., 2010, 2016; Palechor-Tróchez et al., 2018; Vodyanitskii and Savichev, 2017) and extend it to a high-energy tropical setting at the regional scale. The validation of  $L^*$  and  $C^*$  as maturity proxies is directly transferable to nourishment-compatibility assessment, where color matching is an explicit requirement.

Grain morphology provides a direct record of transport pathways and mechanical reworking (Gresina et al., 2023), enabling reconstruction of transport distance and energy across the coast. The combined angularity-roundness analysis is the most internally consistent



**Fig. 8.** Hierarchical clustering dendrogram showing the grouping of sediment samples into four clusters based on multivariate similarity. The structure reflects major patterns in sediment composition, morphology, and depositional conditions.

component of the multi-proxy dataset.

Angularity is spatially structured: low values ( $<0.040$ ) dominate exposed northern sectors (e.g., NRB-1, NRB-3, NRB-6), where grains are well rounded (Powers 4–5) and record prolonged transport and intense abrasion. Higher angularity characterizes sheltered, transitional, and proximally supplied sectors, where abrasion has been insufficient to smooth grain outlines (Prodger et al., 2016).

The inverse angularity–roundness relationship ( $r \approx -0.83$ ), expected from the complementary definitions of the two descriptors, confirms a progressive transformation of grain shape along transport pathways.

As sediments move from source areas toward exposed coastal environments, abrasion systematically reduces angularity and increases roundness, so that grain shape becomes a transport-distance indicator largely independent of grain size (Anthony et al., 2022). This is why morphology forms its own PCA axis (PC3) rather than collapsing onto the energy–maturity axis: two sediments of identical grain size can record very different transport histories.

These morphological patterns yield concrete transport-dynamic inferences. High-energy environments promote longshore transport and repeated reworking, producing well-rounded, low-angularity grains indicative of long effective transport (Shukla et al., 2024), whereas proximal, lower-energy, or sheltered settings preserve angular grains indicative of limited reworking (Vowinckel, 2021). Morphology thus discriminates transport history where color and texture alone are ambiguous, completing the multi-proxy reconstruction.

Caution concerns the asymptotic behavior of grain rounding. Abrasion efficiency decreases as grains become progressively rounder, so that roundness tends to saturate beyond a certain degree of reworking and additional transport produces only marginal morphological change (Krumbein, 1941; Kelly, 1983; Gresina et al., 2023). In very mature systems, morphology may therefore lose sensitivity as a transport-distance proxy, since sands with different reworking histories can converge on similar, near-rounded shapes. In the present dataset this limitation is unlikely to be reached: the well-rounded end-member (Powers class 6) is absent, and Sobel angularity spans a wide, continuous range (0.027–0.109), indicating that the studied sediments still lie on the sensitive portion of the abrasion trajectory. We nevertheless note this saturation effect explicitly as an intrinsic boundary condition of

morphological proxies, most relevant when the framework is transferred to highly mature, far-travelled sand systems.

#### 4.5. Sedimentary facies: A continuum-based classification

Integrating granulometric, colorimetric, morphological, and depositional information allows the definition of five process-based sedimentary facies that describe the continuum of environmental conditions along the coast (Fig. 10). These facies are defined by characteristic combinations of energy, maturity, and grain properties rather than by single thresholds.

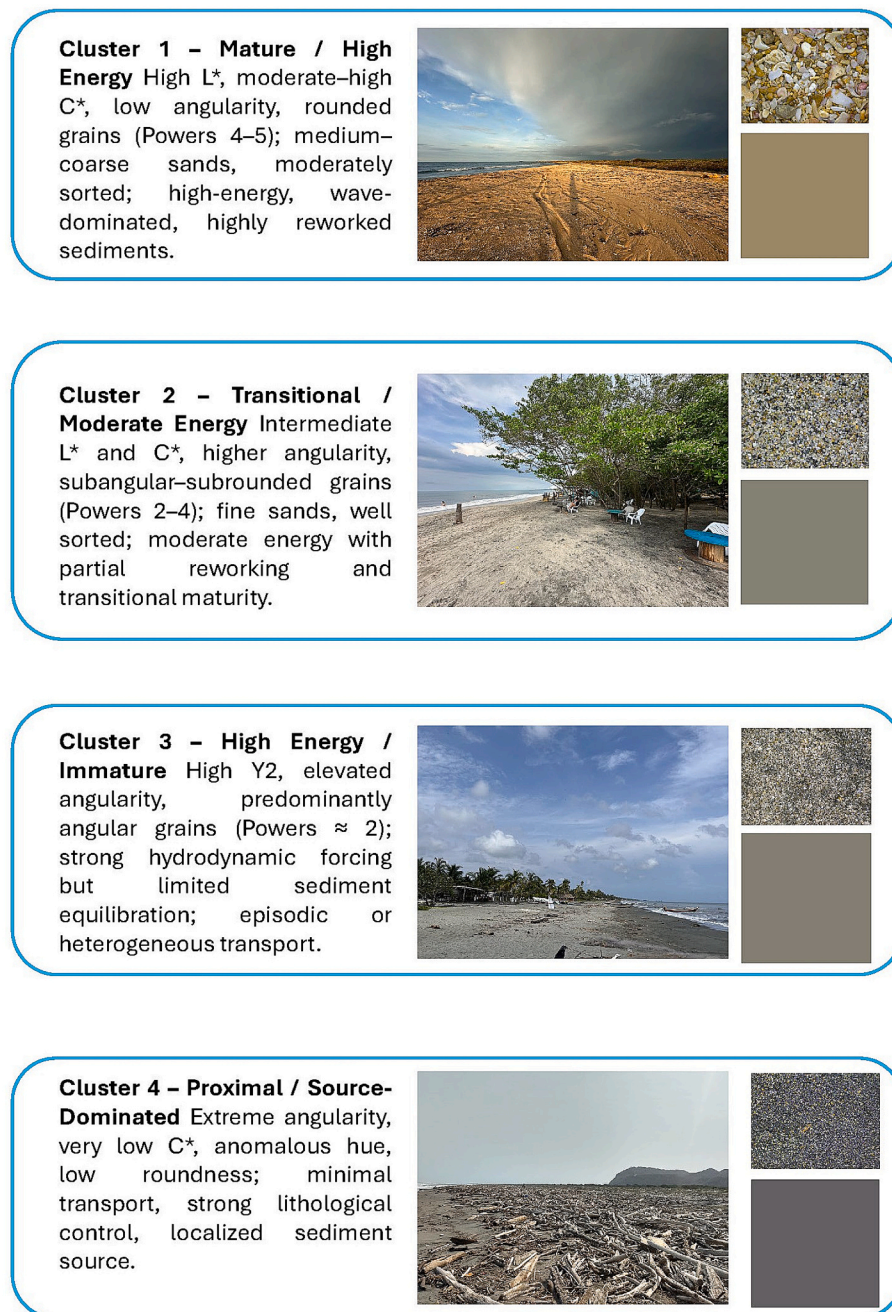
**Facies 1 — High Energy–Mature (HE-M):** high lightness ( $L^* \approx 58$ –68), elevated chroma ( $C^* \approx 12$ –25), low angularity ( $<0.040$ ), and high roundness (Powers 4–5). Grain size is typically medium to coarse sand. These sediments record strong, sustained wave energy and intense reworking, and define the mature end-member (e.g., NRB-2).

**Facies 2 — High Energy–Transitional Maturity (HE-TM):** moderate-to-high optical properties ( $L^* \approx 55$ –62;  $C^* \approx 10$ –15), slightly higher angularity ( $\sim 0.040$ –0.055), and subrounded grains (Powers  $\approx 4$ ), typically in medium sand. They record high energy with incomplete abrasion and partly mixed sources (e.g., NRB-5).

**Facies 3 — Moderate Energy–Transitional Maturity (ME-TM):** intermediate values across all variables ( $L^* \approx 52$ –58;  $C^* \approx 8$ –12; angularity  $\approx 0.050$ –0.065; roundness  $\approx 3$ –4), predominantly fine sand. They record variable energy and incomplete sorting under transitional transport regimes (e.g., NRB-20).

**Facies 4 — Moderate Energy–Immature (ME-IM):** lower optical maturity ( $L^* \approx 50$ –55;  $C^* \approx 5$ –10), higher angularity ( $>0.060$ ), and lower roundness (Powers  $\approx 2$ –3), typically fine and often well-sorted sand. They record sheltered or semi-protected settings with limited transport (e.g., NRB-40).

**Facies 5 — Proximal Source Dominated (PROX):** very high angularity ( $>0.090$ ), low roundness (Powers  $\approx 2$ ), and highly variable, often anomalous optical properties including extremely low chroma. They record minimal transport and strong lithological control by local sources (e.g., NRB-26, NRB-54). Together, these five facies span the full energy–maturity gradient and provide the process-based vocabulary used to interpret the statistical clusters.



**Fig. 9.** Conceptual diagram showing the relationship between sedimentary facies and clustering results. The figure illustrates how five process-based facies are represented within four statistical clusters along the energy-maturity continuum.

A central conceptual outcome of this study is the explicit distinction between statistical clustering and process-based classification, and the recognition that the two are complementary rather than equivalent (Fig. 9; Fig. 11). The mismatch between five facies and four clusters is not an error to be reconciled away but a signal about the underlying structure of the system.

Hierarchical clustering groups samples by overall multivariate similarity and therefore compresses transitional states into broader units. As a result, the intermediate facies, particularly HE-TM, ME-TM, and ME-IM, are distributed across clusters rather than mapped one-to-one: Cluster 2, for example, absorbs most of the transitional samples spanning several facies. Clustering thus represents the dense, continuously varying core of the system as a single statistical group.

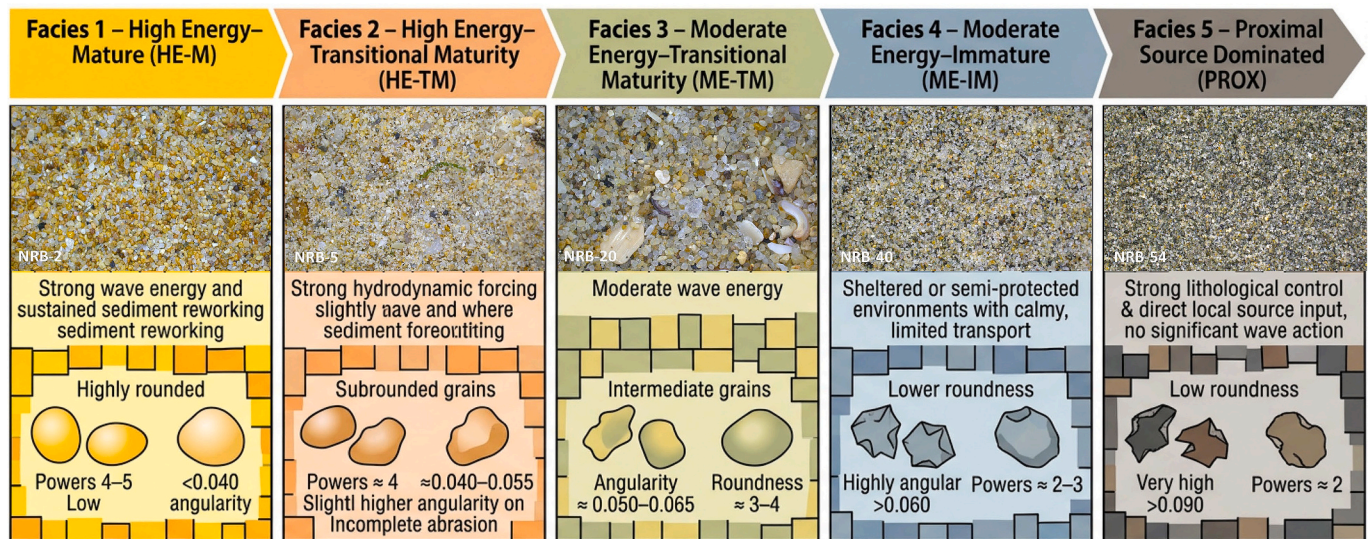
By contrast, the end-members are resolved by both methods. High-

energy mature sediments (HE-M) are consistently captured by Cluster 1, and the proximal end-member (PROX; NRB-26) is isolated as its own cluster (Cluster 4) at high linkage distance. Where signatures are coherent and extreme, statistical and process-based methods converge; where signatures grade continuously, they diverge.

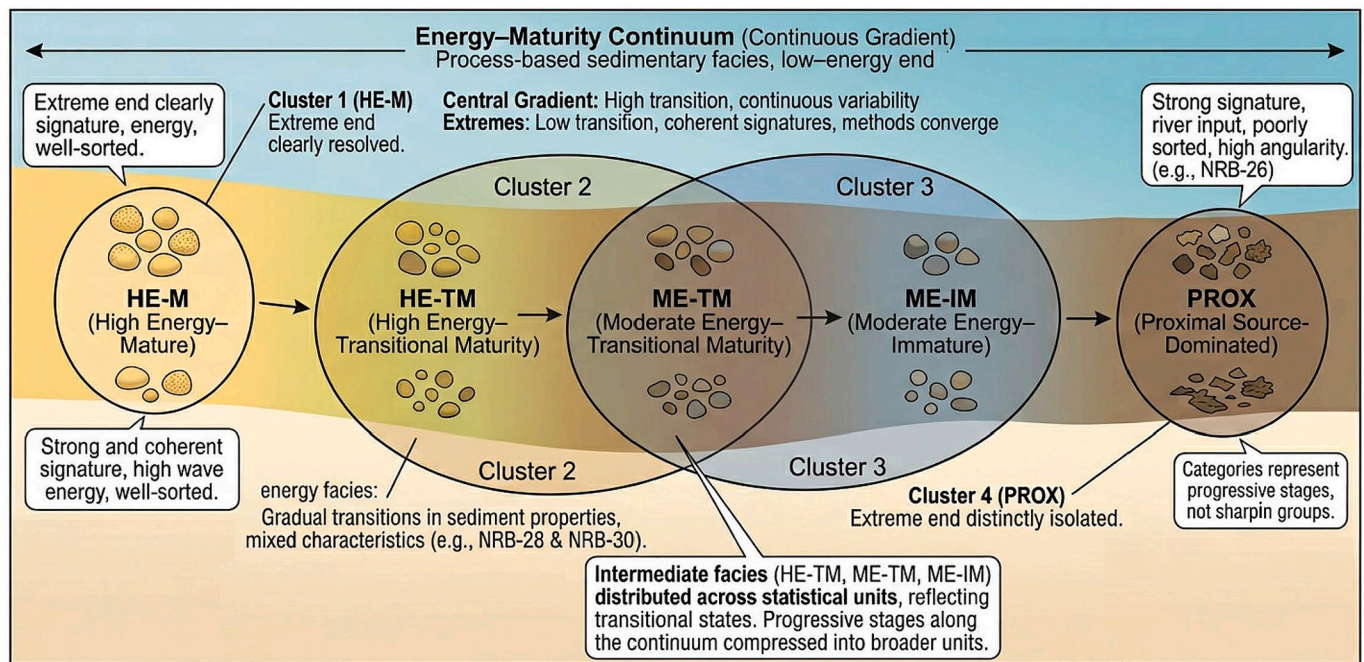
This behavior demonstrates that sediment properties evolve continuously as functions of transport distance, hydrodynamic energy, and sediment supply (Rangel-Buitrago et al., 2025). Grain size, color ( $L^*$ ,  $C^*$ ), and morphology (angularity, roundness) change gradually along the gradient, so that any partition into a fixed number of groups necessarily imposes artificial boundaries on a continuum.

The two perspectives are therefore complementary. Statistical clustering offers a simplified, reproducible summary useful for identifying dominant groupings, while the facies scheme preserves the process-





**Fig. 10.** Process-based sedimentary facies classification illustrating five environmental categories (HE-M, HE-TM, ME-TM, ME-IM, PROX). Each facies is defined by characteristic combinations of energy, maturity, and grain properties.



**Fig. 11.** Conceptual model comparing continuous sedimentary gradients with discrete statistical clustering. The figure highlights the overlap of transitional facies and the convergence of end-member conditions, emphasizing the continuum nature of coastal sediment systems.

based, continuous nature of the variability. Used together, they reveal both the major structure of the dataset and the transitional pathways between end-members.

We conclude that coastal sediments are best interpreted within a continuum framework in which variability is structured by gradients rather than discrete units (Fig. 11). Recognizing this continuum is essential for representing transitional environments accurately and for avoiding the misclassification that rigid, threshold-based schemes can produce in dynamic, well-mixed coastal systems.

#### 4.6. Comparative context and management implications

Placing these patterns in a broader context clarifies which features are general and which are specific to the Colombian Caribbean.

Comparison with analogous coasts across Latin America and beyond shows that the coupling among energy, transport, and sediment properties is a recurrent organizing principle, even where composition and forcing differ.

Along the adjacent Sierra Nevada de Santa Marta coast, Rangel-Buitrago et al. (2018) documented high spatial variability from medium to coarse sands with moderate-to-poor sorting and variable skewness, reflecting strong relief and proximal supply, consistent with the immature, proximally influenced samples identified here in northern and central sectors.

In Spain, Cupul-Magaña et al. (2006) and Asensio-Montesinos et al. (2020) reported moderately-to-poorly sorted beach sands with skewness indicating bidirectional transport and coloration reflecting mineralogy and weathering, paralleling the optical-textural coupling

documented here and supporting the general utility of colorimetry as a maturity proxy.

Comparisons with tropical and subtropical coasts reinforce these consistencies. Along the southern Red Sea, Alharbi et al. (2016) reported medium-to-fine sands with moderate-to-poor sorting and negative skewness, though with strong carbonate influence; and in the United Arab Emirates, Alsharhan and El-Sammak (2004) described medium-to-coarse, moderately-to-well-sorted, negatively skewed carbonate sands. In both, carbonate dominance alters composition while the energy-driven sorting and skewness patterns remain comparable to our siliciclastic system.

Temperate and anthropogenically modified coasts add a further dimension. Statewide analysis of the New Jersey coast (Cerafice et al., 2025) and detailed work at Wildwood and Cape May (Balasuriya et al., 2025) show that nourishment cycles, seasonality, and infrastructure strongly modulate sediment properties, while recreational beaches of Zhanjiang Bay, China (Chen et al., 2025) illustrate the complexity of human-influenced grain-size distributions. These cases echo the role of sediment-supply disruption documented here for the Magdalena system.

Despite differences in composition and forcing, the recurrence of moderately-to-well-sorted sands, systematic skewness, and strong coupling between optical properties and texture across these systems indicates that the energy–maturity organization identified on the Colombian Caribbean is a transferable, general property of wave-dominated coasts rather than a regional peculiarity.

The results of this study provide important insights into the functioning of tropical coastal systems operating under high energy and variable supply. The Colombian Caribbean is a good example of a high-energy, sediment-limited coast in which internal recycling and long-shore transport increasingly govern sediment behavior, and the multi-proxy framework offers a sensitive way to monitor such systems.

At the regional scale, the results highlight the consequences of supply disruption. The reduction of Magdalena fluvial input, largely through the Bocas de Ceniza jetties, has shifted the system toward reliance on reworked and recycled sediments, increasing the importance of long-shore connectivity and making individual compartments more vulnerable to local supply loss.

Globally, comparable dynamics occur in other sediment-limited systems, including arid coasts such as the Arabian Gulf (Alsharhan and El-Sammak, 2004) and parts of the Mediterranean (Asensio-Montesinos et al., 2020), where reduced supply elevates the role of sediment redistribution. The energy–maturity framework developed here provides a common language for comparing such systems.

For monitoring, combining grain-size parameters with optical proxies ( $L^*$ ,  $C^*$ ) and morphological indices (angularity, roundness) enables a more sensitive, reproducible characterization of sediment change over time than texture alone. Because the optical and morphological measurements are rapid and low-cost, they are well suited to repeated, large monitoring campaigns.

For beach nourishment, the results underscore that compatibility requires matching texture, morphology, and color, not grain size alone (Pranzini et al., 2010, 2016). Borrow sediments that match modal grain size but differ in maturity or color can produce visually and behaviorally mismatched beaches; the  $L^*$ – $C^*$  and angularity–roundness signatures defined here provide explicit compatibility criteria.

For erosion management, the framework emphasizes the vulnerability of sediment-limited compartments where stability depends on redistribution rather than replenishment (López-Olmedilla et al., 2022). Sites with immature, proximally controlled signatures are diagnostic of local supply or limited connectivity and can be prioritized for intervention. Overall, the study positions the Colombian Caribbean as a representative high-energy, sediment-limited tropical coast and offers a transferable, reproducible framework for characterizing and managing such systems.

## 5. Conclusions

This study provides the first regional-scale, multi-proxy characterization of coastal sediments along the Colombian Caribbean coast, integrating granulometric, colorimetric, morphological, and statistical analyses. The results demonstrate that sediment variability is not random but structured by a dominant energy–maturity gradient, which acts as the primary control on sediment properties across the region.

Granulometric data confirm that the Caribbean of Colombia coastline is dominated by fine- to medium-sand fractions, reflecting persistent wave-driven reworking under high-energy conditions. However, spatial heterogeneity, particularly in gravel content and sorting, reveals localized influences of sediment sources, geomorphology, and episodic high-energy events. These patterns are consistently reinforced by colorimetric and morphological signals, demonstrating that sediment texture, optical properties, and grain shape are tightly coupled responses to hydrodynamic forcing.

A key contribution of this work is the validation of CIELAB colorimetric parameters ( $L$ ,  $C$ ) as quantitative proxies for sediment maturity and environmental energy. High lightness and chroma values are associated with well-washed, oxidized, and highly reworked sediments, whereas lower values reflect reduced reworking and localized sediment inputs. Similarly, grain morphology provides robust evidence of transport dynamics, with angularity and roundness capturing the cumulative effects of abrasion and transport distance.

The integration of these variables allowed the definition of five process-based sedimentary facies (HE-M, HE-TM, ME-TM, ME-IM, PROX), which describe the continuum of environmental conditions along the coast. In contrast, multivariate statistical analysis grouped the dataset into four clusters, highlighting the distinction between continuous sedimentary gradients and discrete statistical classifications. This dual framework demonstrates that coastal sediment systems are inherently continuous, and that discrete classifications represent simplified approximations of more complex environmental processes.

At the regional scale, the results confirm that the Colombian Caribbean coast operates as a sediment-limited system, where reduced fluvial input (particularly from the Magdalena River) has increased the importance of internal sediment recycling and longshore transport. Despite limited sediment supply, high-energy conditions promote the development of mature sediment characteristics in many sectors, illustrating the dominant role of hydrodynamic forcing.

The patterns identified in this study are consistent with other tropical, temperate, and anthropogenically modified coastal systems, indicating that the coupling between energy, sediment transport, and sediment properties represents a fundamental and transferable characteristic of coastal environments. The multi-proxy framework developed here provides a robust and reproducible tool for sediment characterization, offering clear advantages over traditional single-parameter approaches.

Finally, the findings have direct implications for coastal management, particularly in monitoring, beach nourishment, and erosion mitigation. The integration of granulometric, optical, and morphological indicators enables a more accurate assessment of sediment dynamics, supports the selection of compatible nourishment materials, and improves understanding of system resilience under changing environmental and anthropogenic conditions.

## CRedit authorship contribution statement

**Nelson Rangel-Buitrago:** Investigation, Formal analysis, Conceptualization. **Alex Paternina-Ramos:** Data curation. **William J. Neal:** Investigation, Formal analysis. **Jesús David Pereira Ortega:** Data curation. **Danna Lucia Anaya causado:** Data curation. **Daniel Rincón-Martínez:** Resources, Funding acquisition.



## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Data availability

Data is available in this link: [https://www.dropbox.com/scl/fi/p3ipmax9auasfx0v8bkp/Rangel-Buitrago\\_SEDIMENT-COLLECTION.xlsx?rlkey=bll008m70gsk5diwb2nwwva6b&st=q2t0c75i&dl=0](https://www.dropbox.com/scl/fi/p3ipmax9auasfx0v8bkp/Rangel-Buitrago_SEDIMENT-COLLECTION.xlsx?rlkey=bll008m70gsk5diwb2nwwva6b&st=q2t0c75i&dl=0) Or <https://zenodo.org/records/2059859498593>.

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