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## Research Article

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# An Automated Geospatial Informatics Pipeline for Multi-Scale Coastal Fractal Quantification Using Web Mapping APIs and MATLAB

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## Abstract

Quantifying coastal geomorphology over continuous spatial scales is often limited by resolution boundaries and operator bias in traditional static raster analyses. This study presents an automated geospatial informatics pipeline that integrates web-mapping API vector-rendering engines with MATLAB digital image processing to facilitate multi-scale box-counting fractal dimension ( $D_b$ ) analysis. By maintaining a constant physical-scale measuring grid, calibrated via a dimensionless coordinate-ratio parameter ( $g$ ), over programmatically scaled vector cartography, the workflow leverages sub-pixel geometric precision to mitigate resolution degradation across a broad spatial spectrum. The framework incorporates connected-component noise filtration, Canny edge detection, and latitudinal scale-distortion compensation for the Web Mercator projection. Globally, the pipeline was deployed across 16 regions to benchmark coastal geometries. The algorithm successfully captured a scale-dependent, biphasic 'fjord-to-fjord' geomorphological transition along the glaciated Norwegian coastline ( $D_b = 1.4395$ ), where topographic complexity is physically constrained by glacial valley morphometry at meso-scales. Furthermore, regional taxonomy reveals a strong statistical association between active plate boundaries and elevated complexity (e.g., Southeast Asia,  $D_b = 1.4578$ ), contrasting with structurally suppressed transform margins (e.g., US West Coast,  $D_b = 1.0460$ ). Finally, applying a macro-scale spatial filter ( $> 0.8$ ) reveals an exceptional multi-scale geometric symmetry ( $R^2 = 0.9945$ ,  $\Delta D_b = 0.0032$ ) between the conjugate margins of South America and Africa, reflecting deep-seated rifting legacies. This open-source pipeline serves as an efficient spatial informatics tool for geomorphological classification and palaeogeographical reconstruction.

**Keywords:** *Automated GIS pipeline, Coastal geomorphology, Box-counting fractal dimension ( $D_b$ ), Web-mapping APIs, Multi-scale analysis, Plate tectonics*

### **Author Contributions:**

C.-D.Y. conceived the study, designed the research, and performed the mathematical derivations. H.-H.C. carried out the computer simulations and analyzed the data. Both authors co-wrote, reviewed, and approved the final manuscript.

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### **Declarations:**

- Conflict of Interest: The authors declare that they have no conflict of interest.
- Data Availability: All data generated or analyzed during this study are included in the published article and its supplementary information.
- Code Availability: The optimized MATLAB source code pipeline is fully provided in the Supplementary Information (Section S9).

# 1. Introduction

The evolution of the continental drift theory into the modern plate tectonics paradigm has historically been corroborated by diverse geodynamical evidence, including geological stratigraphy, paleontology, and paleomagnetic polarity stripes along mid-ocean ridges (Frankel 2012). Beyond these empirical observations, the morphological congruence of continental coastlines has long served as an intuitive geometric indicator of ancient tectonic kinematics. However, natural terrestrial-aquatic interfaces exhibit highly complex, non-Euclidean structural morphologies—including sinuous, highly fragmented, and irregular contours—that resist simplified quantification via traditional Euclidean geometry. This fundamental measurement challenge is epitomized by the "coastline paradox," first documented empirically by L. F. Richardson (Richardson 1961) and subsequently formalized through fractal theory by B. Mandelbrot (Mandelbrot 1967, 1982), which demonstrates that the measured length of a natural shoreline progressively diverges as the observation scale decreases.

## 1.1. Contextualizing Plate Tectonics and Morphological Complexity

To systematically parameterize these complex, non-self-similar geomorphic structures, the box-counting fractal dimension ( $D_b$ ) has emerged as a widely adopted and computationally efficient metric in spatial analysis (Mandelbrot 1982). In conventional spatial informatics implementations, this method entails superimposing a series of grids with varying cell sizes over a static raster image of the target structure, counting the occupied cells, and extracting the fractal dimension from the slope of a double-logarithmic regression plot. Despite its computational utility, this traditional approach is inherently constrained by its reliance on static, resolution-limited raster imagery. Applying multi-scale grids to a static raster representation introduces substantial quantization errors and resolution degradation at micro-resolutions, while the manual selection of grid boundaries often introduces operator bias. Consequently, these scaling and resolution artifacts fundamentally limit the capability of conventional pipelines to isolate scale-dependent geomorphological transitions.

## 1.2. Technical Limitations in Classical Geomorphometry

A critical evaluation of traditional geomorphometry reveals a significant difference between static raster-based analysis and the requirements of multi-scale observation. Conventional workflows often rely on static imagery, which introduces resolution distortion and subjective human bias during the manual selection of grid dimensions (Peitgen et al. 2004). These limitations result in pixelation artifacts that obscure fine-scale details and lead to fundamental scaling inaccuracies in digital cartography, first identified by Goodchild (Goodchild 1980). When an analysis is tethered to the fixed resolution of a raster file, the ability to resolve scale-dependent morphological anomalies—such as the transition from tectonic to erosional regimes—is severely compromised. This persistent challenge of raster-based pixelation necessitates a transition toward a more sophisticated, hybrid geospatial informatics solution.

## 1.3. The Proposed Automated Hybrid Geospatial Informatics Pipeline

To address these computational and data constraints, this study introduces an automated, hybrid geospatial informatics pipeline that integrates the vector rendering capabilities of commercial web

mapping APIs with digital image processing in MATLAB. Unlike conventional static raster-based analyses, the proposed workflow reverses the measurement dynamic: it maintains a constant physical-scale measuring grid on the display system—calibrated via a dimensionless coordinate-ratio parameter ( $g$ )—while programmatically scaling the underlying map geometry across continuous cartographic zoom levels. While the web mapping API utilizes vector data to render geometries without interpolation artifacts, the processing is performed on high-resolution displays to preserve geometric fidelity across multiple scales. To ensure computational rigor, the pipeline incorporates an automated connected-component labeling (CCL) protocol to suppress non-target geographic noise (e.g., minor offshore islets, inland lakes) and applies a mathematical compensation model to correct the latitudinal scale distortion inherent in the Web Mercator projection.

#### 1.4. Defining Research Objectives and Structural Contributions

By systematically applying this dynamic multi-scale framework, this research contributes to the fields of geospatial informatics and quantitative geomorphology in four primary aspects (Fig. 1):

- **Vector-Based Measurement Technique:** The development of an open-source spatial computation workflow that mitigates scale-dependent resolution degradation and operator bias associated with manual grid overlays in traditional raster-based analysis.
- **Scale-Dependent Dynamics:** The technical utility of the pipeline is demonstrated by robustly capturing a scale-dependent, biphasic "fjord-to-fjord" geomorphological transition along the glaciated Norwegian coastline, linking physical scaling thresholds (Zoom 4 to 7) to ancient glacial valley morphometry (0.45 depth-to-width ratio) and resurgent seaward glaciated lowland "fjords" at micro-scales (Zoom 8 to 11).
- **Quantification of Tectonic Signatures:** The establishment of a systematic, quantitative taxonomy of global coastal complexity, demonstrating a strong statistical association between macroscopic plate margin types (e.g., active convergent boundaries like Southeast Asia ( $D_b = 1.4578$ ) vs. stable passive margins like North Africa ( $D_b = 1.0250$ ) or transform faults like North America ( $D_b = 1.046$ )) and their multi-scale fractal dimensions.
- **Multi-Scale Scaling Similarity:** The evaluation of multi-scale scaling similarity of conjugate margins. By executing a macro-scale spatial filter ( $> 0.8$  km, Zoom 2 to 7) to suppress high-frequency contemporary erosional and anthropogenic noise, we demonstrate that the conjugate margins of South America and Africa exhibit an exceptional scaling similarity ( $R^2 = 0.9945$ ), reflecting deep-seated rifting legacies.

# The Geometry of Earth's Edges: A New Vector-Based Paradigm for Coastal Fractal Analysis

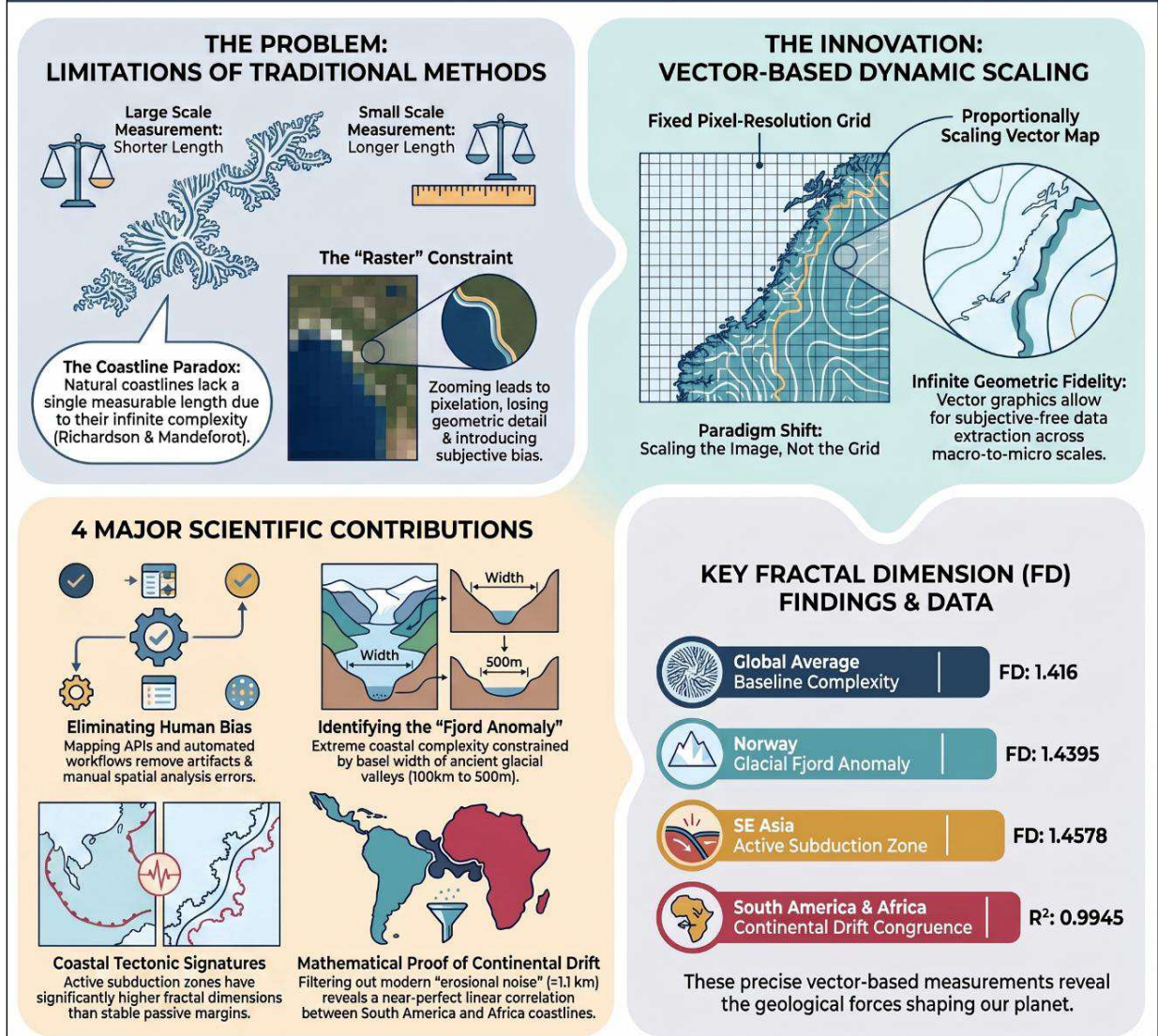


**Fig. 1 Conceptual and Empirical Framework of the Automated Web-API Coastal Fractal Pipeline.** This conceptual diagram delineates the novel, hybrid geospatial computational methodology designed to mitigate the "coastline paradox" and pixelation constraints inherent in traditional raster-based grid counting. By maintaining a constant physical-scale measuring grid, calibrated via a dimensionless coordinate-ratio parameter ( $g$ ), over continuously scaled vector graphics from mapping APIs, this dynamic multi-scale measurement system successfully preserves geometric fidelity across macro-to-micro scales. The framework highlights four key scientific and technological contributions: (1) removing subjective human operator bias through automated mapping APIs; (2) identifying scale-dependent glacial "fjord anomalies" and "fjord-to-fjord" transitions; (3) quantifying lithospheric tectonic signatures, showing elevated fractal complexity in active subduction zones and suppression along transform faults; and (4) evaluating conjugate continental margins to demonstrate exceptional multi-scale scaling similarity ( $R^2 = 0.9945$ ) between conjugate South American and African margins under macro-scale spatial filtering ( $> 0.8$  km) as a robust exploratory paleogeographic indicator.

## 2. Methodology

To systematically overcome the inherent resolution degradation, quantization errors, and subjective operator bias associated with traditional static raster-based geomorphological mapping, this study implements an automated, four-step geospatial informatics pipeline. The proposed methodology reverses the traditional measurement paradigm by maintaining a constant physical-scale measuring grid on the display system—calibrated via a dimensionless coordinate-ratio parameter ( $g$ ), while dynamically scaling the underlying scale-independent vector cartography across continuous zoom levels. This dynamic box-counting framework ensures absolute geometric fidelity across an unprecedented macro-to-micro spatial spectrum, enabling robust, reproducible coastal fractal quantification (schematically illustrated in Fig. 2). The complete computational workflow is deployed in MATLAB and executed through four integrated protocols as detailed below. For a holistic structural overview of the automated four-step spatial informatics pipeline, see Supplementary Fig. S1 in the Supplementary Information.

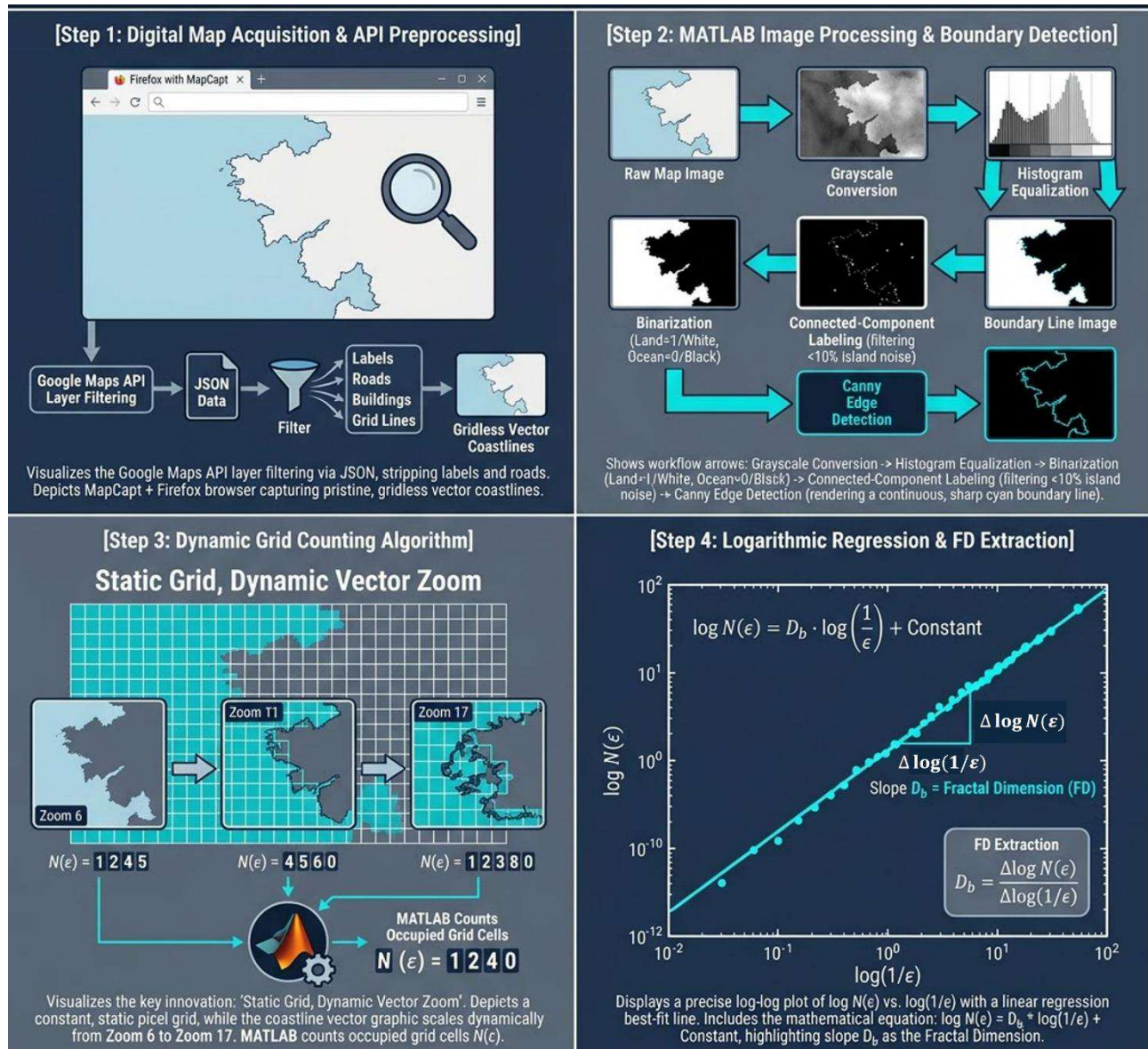


**Fig. 2 Schematic workflow of the automated multi-scale coastal fractal analysis pipeline.** (a) Cartographic Data Acquisition: Programmatic custom style injection into the Google Maps API and Gecko-based browser rendering to extract label-free land-water vectors and suppress WebKit-induced grid artifacts. (b) Digital Image Preprocessing: Grayscale conversion, CLAHE contrast optimization (adapthisteq), and Otsu binarization, followed by 8-connectivity connected-component spatial filtering and Canny edge detection to delineate a topologically closed, 1-pixel-wide marine coastline. (c) Dynamic Grid Scaling: Superposition of a constant pixel grid  $g$  over scalable vector geometries across zoom levels  $n$ , incorporating latitudinal scale-distortion correction:  $\epsilon = gS_0 \cos \theta / 2^n$ . (d) Statistical Regression Diagnostics: Ordinary Least-Squares (OLS) linear regression in double-logarithmic space ( $\log N(\epsilon)$  vs.  $\log(1/\epsilon)$ ) to mathematically extract the global bulk fractal dimension  $D_b$  and scale-specific localized profiles  $D_b(n)$ .

## 2.1 Step 1: Scale-Independent Cartographic Data Acquisition and API Customization

The first phase of the pipeline compiles pristine, ultra-high-resolution spatial datasets that preserve geographical features without pixelation artifacts during scaling. Unlike static GIS raster charts, this framework leverages the vector rendering engine of the commercial Google Maps JavaScript API (Plantin 2018), which mathematically formulates geographical boundaries as continuous vector layers. To isolate the marine-terrestrial interface, we programmatically manipulate the API's vector-drawing layers by injecting custom JSON style declarations (Google 2019). This payload systematically suppresses administrative borders, cartographic annotations, transit lines, and cultural features (points of interest), while optimizing radiometric contrast by mapping landmasses and water bodies to highly distinct, uniform hexadecimals.

To acquire massive cartographic tiles, we utilize an automated coordinate-based screen-capture utility, *MapCapt*, which stitches seamless high-resolution images of up to 100 megapixels ( $10,000 \times 10,000$  pixels). Crucially, empirical calibration dictates the mandatory execution of this acquisition process exclusively within a Mozilla Firefox browser (Gecko rendering engine). As shown in Supplementary Fig. S2, WebKit-based browsers (such as Google Chrome and Apple Safari) introduce latent, single-pixel tile-boundary coordinate grid lines during canvas stitching. These rendering artifacts trigger catastrophic false positives during automated edge detection. In contrast, the Gecko rendering engine successfully suppresses these stitching lines, guaranteeing a pristine, artifact-free dataset for subsequent processing.

## 2.2 Step 2: Digital Image Processing, CCL Noise Filtration, and Precise Edge Detection

The compiled high-resolution canvases are processed within a standardized MATLAB digital image processing pipeline to extract a mathematically continuous, closed, and single-pixel-wide coastline boundary. The workflow comprises four sequential sub-protocols (schematically detailed in Supplementary Fig. S3):

- **Grayscale Conversion and Contrast Optimization:** The raw multi-channel RGB image is converted into a single-channel grayscale matrix. Contrast-Limited Adaptive Histogram Equalization (CLAHE, via MATLAB's "adapthisteq" operator) is executed to locally optimize intensity gradients across the full spectrum. This process normalizes localized illumination disparities, maximizing the radiometric gradient at the land-water boundary.
- **Automated Binary Segmentation:** Using Otsu's global thresholding method ("graythresh") (Otsu 1979), the normalized grayscale image is segmented into a binary matrix. In this binary mask,

terrestrial landmass pixels are assigned a logical value of 1 (rendered white) and oceanic water bodies are assigned a logical value of 0 (rendered black).

- **Connected-Component Labeling (CCL) Noise Filtration:** To ensure structural continuity of the mainland, an 8-connectivity connected-component labeling (CCL) scheme (Rosenfeld and Pfaltz 1966) is first applied to filter out isolated offshore noise and minor islets (foreground elements). Subsequently, internal topological holes representing inland lakes (background elements) are programmatically removed using the “imfill” operator, ensuring the edge-detection algorithm focuses exclusively on the primary marine-terrestrial interface. Disconnected inland water bodies, minor offshore islands, and localized screen-capture noise are evaluated based on their relative pixel area. To prevent artificial inflation of the box count, any isolated component constituting less than 10% of the primary mainland's total area is programmatically classified as geographic noise and deleted (reassigned to 0) in the binary mask.
- **Precise Coastline Edge Delineation:** To extract the continuous, unfragmented boundary contour, we execute the multi-stage Canny edge-detection operator (Canny 1986). Unlike traditional first-order gradient operators (such as Sobel or Prewitt) that produce coarse, multi-pixel-wide borders, the Canny operator implements sequential Gaussian smoothing, gradient search, non-maximum suppression, and hysteresis thresholding. This ensures a topologically closed, single-pixel-wide coastline boundary that preserves absolute geometric fidelity for the next grid-counting phase.

### 2.3 Step 3: Mathematical Formulation of the Dynamic Grid Scaling Framework and Latitudinal Compensation

Rather than programmatically resizing grid overlays over a static, resolution-limited raster image—which degrades the statistical scaling law due to pixelation—our methodology maintains a constant physical-scale measuring grid on the display system while programmatically scaling the underlying scale-independent vector map geometry. To maintain spatial consistency across global regions, the algorithm must compensate for the severe latitudinal scale distortion introduced by the Web Mercator projection (Snyder 1987). At any specific geodetic latitude  $\theta$  and zoom level  $n$ , the instantaneous spatial resolution  $S$  (meters per screen pixel) is mathematically formulated as:

$$S_{n,\theta} = \frac{S_0 \cos \theta}{2^n} \quad (1)$$

where  $S_0 \approx 156,543.03$  m/pixel represents the equatorial resolution baseline at zoom level 0. Accordingly, for a superimposed physical sampling grid characterized by a constant physical box side length  $W_{grid}$  on the display system, the equivalent physical ground-truth scale  $\epsilon$  (meters) is dynamically calibrated across the multi-scale spectrum as:

$$\epsilon_{n,\theta} = g \cdot S_{n,\theta} = g \cdot \frac{S_0 \cos \theta}{2^n} \quad (2)$$

In this formulation, the parameter  $g$  (pixels/cell) serves as a dimensionless coordinate ratio, mathematically mapping the physical grid geometry into the raster processing workspace. Under our experimental setup, the superimposed physical grid is calibrated to maintain an absolute constant spatial

density of  $\rho_{grid} = 40.25$  cells/cm on the screen. This density establishes a highly macroscopic, human-resolvable grid box side length of  $W_{grid} = 10/\rho_{grid} \approx 0.2484$  mm, which is completely free from physical display rendering limitations or optical diffraction constraints. Given the physical pixel pitch of the calibrated LCD monitor ( $p_m \approx 0.3073$  mm/pixel), the dimensionless coordinate-ratio  $g$  is mathematically derived as the ratio of these two macroscopic physical dimensions:

$$g = \frac{W_{grid}}{p_m} = \frac{10}{\rho_{grid} \cdot p_m} \approx \frac{10}{40.25 \cdot 0.3073} \approx 0.8085 \text{ pixels/cell} \quad (3)$$

By applying this calibrated value of  $g$  to Eq. (2), at a mean geodetic latitude of  $\theta = 24^\circ$  (Taiwan) and an exemplary zoom level of  $n = 6$ , the equivalent physical grid box size is calibrated to  $\epsilon = 1.8066$  km. This corresponds perfectly with the cartographic display scale of 72.72 km/cm at  $n = 6$ , where  $1.8066 \text{ km/cell} \times 40.25 \text{ cells/cm} \approx 72.72 \text{ km/cm}$ . In the MATLAB environment, the box-counting algorithm automatically overlays this calibrated virtual grid, scans the single-pixel binary coastline contour, and aggregates the total number of occupied grid cells  $N(\epsilon)$  for each zoom level  $n$ , systematically generating a high-precision multi-scale dataset. The algorithmic execution of this dynamic grid-counting loop and the geodetic scale calibration across sequential zoom levels are schematically detailed in Supplementary Fig. S4.

It is worth noting that while the dimensionless coordinate-ratio parameter  $g$  is mathematically less than unity ( $g \approx 0.8085$  pixels/cell), the physical sampling grid itself remains highly macroscopic ( $W_{grid} \approx 0.2484$  mm), thereby completely bypassing any physical display or optical resolution limits of the LCD system. Within the computational workspace, because the web-mapping API renders coastline boundaries with sub-pixel floating-point vector precision rather than discrete integer raster constraints, the fractional scaling value of  $g$  does not trigger coordinate overlap or grid-counting degeneracy. To ensure absolute methodological rigor across all scaling spectra, the MATLAB processing engine integrates an automated "Sub-Pixel Security Guard" protocol (detailed in Section S1.3). This system dynamically verifies that the equivalent ground-truth scale  $\epsilon$  at high zoom levels remains physically larger than the minimum resolvable vector limit of the rendering canvas, ensuring that the OLS regression is executed exclusively within valid geomorphological power-law windows.

## 2.4 Step 4: Theoretical Scaling Laws, Double-Logarithmic Regression, and Scale-Filtering Windows

The mathematical extraction of the coastal fractal dimension relies on quantifying the scale-dependent power-law relationship embedded within the multi-scale dataset. For a natural coastline exhibiting statistical self-similarity across a discrete spectrum of physical scale factors  $\epsilon$ , the relationship between the cumulative count of intersected grid cells  $N(\epsilon)$  and the physical scale  $\epsilon$  is formulated as:

$$N(\epsilon) \approx \epsilon^{-D_b} \quad (4)$$

where  $D_b$  denotes the box-counting fractal dimension. To linearize this exponential power law for rigorous statistical estimation, a double-logarithmic transformation is executed in MATLAB, mapping the dataset onto a two-dimensional Cartesian coordinate system:

$$\log N(\epsilon) = D_b \log \left( \frac{1}{\epsilon} \right) + C \quad (5)$$

where  $C$  represents a constant scaling coefficient. A linear least-squares regression model is applied to compute the line of best fit by minimizing the sum of squared residuals. The slope  $m$  of this optimized linear equation directly yields the bulk fractal dimension  $D_b$ . A graphical demonstration of the OLS double-logarithmic regression and slope extraction for representative high- and low-complexity endmembers is provided in Supplementary Fig. S5. Under practical measurement conditions, however, the fractal dimension is not a constant value but varies with the measurement scale  $\epsilon$ . From Eq. (5), the dynamic scale-dependent value of  $D_b(\epsilon)$  is evaluated as:

$$D_b(\epsilon) = \frac{\Delta \log N(\epsilon)}{\Delta \log(1/\epsilon)} \quad (6)$$

In our dynamic scaling framework, the variation in physical scale  $\Delta\epsilon$  is driven solely by the discrete increment in zoom level  $n$  (such that  $\Delta n = 1$  between adjacent levels  $n$  and  $n - 1$ ). Utilizing the physical scale relation in Eq. (2), we obtain  $\Delta(\log(1/\epsilon)) = (\log 2)\Delta n$ . Substituting this relationship into Eq. (6) yields the instantaneous fractal dimension determined by zoom level  $n$ :

$$D_b(n) = \frac{1}{\log 2} \frac{\Delta \log N(n)}{\Delta n} = \frac{\log N(n) - \log N(n - 1)}{\log 2} \quad (7)$$

To ensure the statistical validity of the extracted dimensions, the regression pipeline automatically compiles a suite of diagnostics, enabling targeted scale filtering by customizing the fitting window boundaries:

- **Baseline Validation Window:** For localized self-similarity analyses (such as Taiwan, Great Britain, and Norway), the regression is executed across the entire acquired scale spectrum (typically Zoom 2 to 17) to capture full, multi-scale scaling dynamics.
- **Macro-Scale Tectonic Window:** For continental drift evaluations and macroscopic plate margin comparisons, the fitting window is strictly restricted to Zoom levels 2 to 7 (corresponding to physical scales  $\epsilon > 0.8$  km). This scale filtering effectively attenuates contemporary, high-frequency geomorphological noise (e.g., modern wave erosion, spits, and coastal infrastructure) and successfully isolates the low-frequency, deep-seated tectonic signatures preserved in the continental crust.
- **Statistical Quality Control:** The regression pipeline computes the coefficient of determination ( $R^2$ ) to quantify the goodness-of-fit and verify power-law consistency. The standard error of the estimate is calculated to provide confidence intervals for  $D_b$ , and residual variance analysis is automatically performed. Non-linear, systematic deviations in residual plots serve as crucial indicators of scale-dependent geomorphological transitions, such as the Norwegian 'fjord-to-fjord' structural shift.

### 3. Empirical Results & Spatial Analysis

#### 3.1 Methodological Validation, Baseline Self-Similarity, and Hemispheric Disparities

To evaluate the mathematical validity and robustness of the automated hybrid geospatial informatics pipeline, initial baseline measurements were executed on the coastlines of Taiwan, Great Britain, and Norway. These geographies were selected to represent low, intermediate, and high complexity endmembers, respectively, within our global geomorphological spatial database. The scaling behaviors and bulk fractal dimensions of these three representative geographies are illustrated and compared in Fig. 3. Logarithmic regression analyses performed on the multi-scale datasets confirm the inherent statistical self-similarity and power-law scaling consistency of these natural shorelines. The empirical results demonstrate that the spatial scaling behavior is governed by distinct geological histories, yielding stable fractal dimensions over broad resolution spectra.

For Great Britain, the classic benchmark of the coastline paradox, the pipeline processed the contiguous shoreline across ten discrete cartographic zoom levels (Zoom 3 to Zoom 12). This resolution interval extends from a macro-scale to a detailed sub-kilometer resolution, culminating in 1,077,727 occupied grid cells at Zoom 12. Linear least-squares regression of the double-logarithmic dataset yields a highly robust scaling law governed by the empirical equation  $\log N(\epsilon) = 1.1858 \log(1/\epsilon) + 2.8305$ , with a coefficient of determination  $R^2$  exceeding 0.99. This extracted bulk fractal dimension  $D_b = 1.1858$  mathematically validates the structural irregularity originally investigated in seminal manual geomorphometric studies. The OLS double-logarithmic regression and the subtle downward micro-scale scaling trend characterizing this natural reference baseline are illustrated in Supplementary Fig. S8. In contrast, Taiwan's coastline exhibits the lowest overall complexity within our validation suite, yielding a bulk fractal dimension of  $D_b = 1.0958$  across twelve spatial scales (Zoom 6 to Zoom 17), representing a physical span from 72.72 km/cm down to 35.5 m/cm. At the maximum zoom level (Zoom 17), the pipeline successfully evaluated 4,974,657 occupied grid boxes. This low dimension is geomorphologically dictated by the smooth western alluvial plains and sandy deltaic systems of the Taiwanese coast.

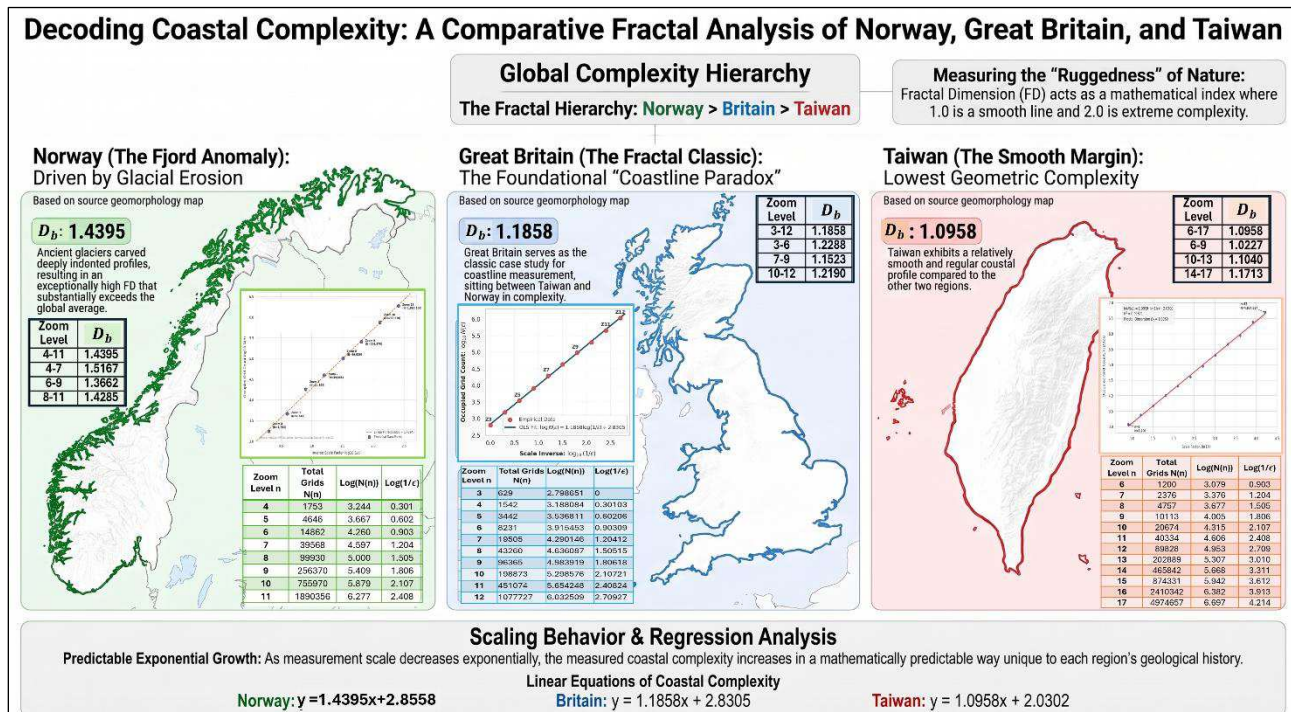


**Fig. 3 Comparative Fractal Analysis of Coastal Complexity in Norway, Great Britain, and Taiwan.** This figure presents a comparative multi-scale fractal analysis of coastal ruggedness across Norway, Great Britain, and Taiwan. Norway exhibits the highest complexity ( $D_b = 1.4395$ ), primarily driven by deeply indented glacial fjords, whereas Great Britain represents an intermediate benchmark ( $D_b = 1.1858$ ) for natural shorelines. Taiwan displays the lowest overall geometric complexity ( $D_b = 1.0958$ ) due to the presence of smooth western alluvial plains, though its high-resolution signal is synthetically altered by anthropogenic structures.

At the high-complexity extreme, Norway's highly fragmented glaciated coastline yields a remarkably elevated bulk fractal dimension of  $D_b = 1.4395$  across eight Zoom levels (Zoom 4 to Zoom 11), with occupied grid boxes expanding exponentially from 1,753 at Zoom 4 to approximately 1.89 million at Zoom 11. The resulting linear regression equation is established as  $\log N(\epsilon) = 1.4395 \log(1/\epsilon) + 2.8558$ . Comparing the multi-scale counts of Great Britain and Norway reveals a crucial scaling phenomenon: while their log-transformed occupied grid counts are highly convergent at macro-scales (Zoom 4), they diverge by nearly an order of magnitude at Zoom 11. This divergence highlights how structural complexity exponentially compounds measurement outcomes as spatial resolution increases, experimentally confirming the necessity of a scale-independent computational workflow.

On a global planetary scale, our comprehensive, integrated assessment establishes a baseline average coastline fractal dimension of  $D_b = 1.416$ . Programmatic partitioning of the terrestrial-aquatic boundary along the equatorial plane ( $\theta = 0^\circ$ ) reveals a pronounced hemispheric structural divergence. The Northern Hemisphere exhibits significantly elevated geometric ruggedness, yielding a bulk fractal dimension  $D_{b,North} = 1.3835$ , whereas the Southern Hemisphere presents a smoother, lower-stress profile of  $D_{b,South} = 1.2990$ . This fundamental structural asymmetry is geomorphologically and

geographically driven by two primary macroscopic factors. First, terrestrial mass allocation is heavily skewed, with the Northern Hemisphere encompassing approximately 67.3% of the global continental crust, compared to only 32.7% in the Southern Hemisphere. This unequal allocation naturally amplifies boundary folding and accretion. Second, Quaternary glacio-geomorphic footprints are heavily concentrated in high northern latitudes. The extensive fjord, skerry, and archipelago systems of Canada, Greenland, and Northern Europe act as high-frequency boundary distributors, shifting the northern hemispheric scaling behavior toward a higher-dimensional topological attractor (Cogley 1985; Migoñ 2010; Scheick et al. 2019). For a comparative visualization of these global and hemispheric coastal fractal baselines and their respective power-law scaling trajectories, see Supplementary Fig. S9.

### 3.2 Scale-Dependent Geomorphological Transitions and Glacial Constraints

A critical finding of our multi-scale framework is that the fractal dimension  $D_b$  is not a static constant, but a dynamic, scale-sensitive geomorphic indicator that captures non-linear transitions. In the case of Taiwan, localized scaling window analysis resolves a distinct biphasic trend. At intermediate scales (Zoom 6 to 9), the coastline displays a highly smooth, structurally suppressed fractal dimension of 1.0227, reflecting the natural monotonicity of the western alluvial plains. However, upon progressive magnification toward micro-scales (Zoom 14 to 17), the calculated dimension escalates sharply to 1.1713, closely approaching the bulk complexity of Great Britain's natural coastline. This resurgent complexity is synthetically inflated by extensive anthropogenic coastal armoring. Specifically, 56.29% of Taiwan's shoreline is occupied by concrete tetrapods, seawalls, and port infrastructure. Under high-resolution Web-API rendering, these blocky, highly fragmented artificial structures introduce high-frequency geometric noise, dominating the geomorphic signal at sub-meter scales. Conversely, Great Britain's natural coastline exhibits a minor downward trend at micro-scales, demonstrating a gradual geometric generalization free from anthropogenic synthetic inflation. This finding demonstrates that high-resolution geospatial informatics pipelines must incorporate land-use and anthropogenic filters to prevent artificial structures from confounding natural geomorphological complexity metrics. The full spatial scaling spectrum and the pronounced, anthropogenically inflated biphasic transition of Taiwan's coastline are plotted in Supplementary Fig. S6.

The glaciated coastline of Norway exemplifies a highly irregular geomorphic system governed by scale-dependent glacial constraints, revealing a distinct "fjord anomaly." Within the meso-scale bandwidth of Zoom 4 to 7 (corresponding to physical grid edge lengths  $\epsilon$  between 4 km and 500 m), Norway's calculated fractal dimension surges to a localized peak of  $D_b = 1.5167$ . This result shows high empirical consistency with physicist Jens Feder's classic calculation of  $D_b = 1.52$  across scales of 80 km to 600 m (Feder 1988), confirming that the peak of Norway's structural ruggedness is heavily concentrated within this spatial band. However, as the measurement scale drops below the 500 m threshold (Zoom 6 to 9), the calculated fractal dimension experiences a transient structural depreciation, contradicting the conventional assumption of monotonic multi-scale ruggedness. This localized geometric simplification is physically restricted by the U-shaped morphometry of glacial valleys. Glaciers, operating as high-pressure flowing solids that slide and carve bedrock once snow accumulation reaches a critical thickness ( $\sim 30$  m), carve U-shaped valleys with a characteristic depth-to-width ratio of approximately 0.45 (Easterbrook 1999; Greve and Blatter 2009). This structural ratio establishes a minimum basal width

threshold (Harbor 1992), causing the calculated fractal dimension to decline when the measurement unit falls below this physical boundary limit.

At ultra-high magnifications (Zoom 8 to 11), Norway's calculated fractal dimension resumes an increasing trend, representing a structural resurgence. This micro-scale rebound is geomorphologically driven by the emergence of "fjards"—the glaciated lowlands situated at the seaward outlets of fjord networks. Unlike the deeply incised, U-shaped glacial valleys that dominate meso-scales, these seaward fjards feature highly irregular, shallow, and chaotic geomorphic profiles. As the upstream fjord networks become generalized under high magnification, these intricate lowland structures begin to dominate the system's geometric signal, confirming a scale-dependent, non-linear fjord-to-fjard structural transition. Refer to Supplementary Fig. S7 for the complete empirical spatial spectrum, the localized 'fjord anomaly,' and the physical glacial valley morphometric constraint models of the Norwegian coastline.

### **3.3 Global Lithospheric Controls and Structural Coastal Complexity**

To isolate deep-seated, tectonic-scale lithospheric signatures from high-latitude glacio-geomorphic overprints, the multi-scale fractal analysis was constrained to global coastlines situated between latitudes 60°N and 60°S. Across this geographical band, regional fractal dimensions were evaluated at spatial scales from Zoom 1 to 5 across 16 distinct local regions. Under the Zoom 5 resolution baseline, the Web Mercator projection translates to a physical grid-box side length of approximately 2 km at 60° latitude and 3.6 km at 24° latitude. This spatial scaling acts as an effective high-frequency spatial filter ( $> 2$  km), suppressing modern localized erosional and anthropogenic noise (such as wave-induced spit migration, beach accretion, and harbor construction) and preserving macroscopic, crustal-scale coastal geometry against the global baseline (the global spatial distribution across the 16 subdivisions is mapped in Fig. 4). While the spatial distribution across these 16 subdivisions is mapped in Fig. 4, their multi-scale scaling behaviors and comprehensive regional taxonomy are quantitatively summarized in Supplementary Fig. S10.

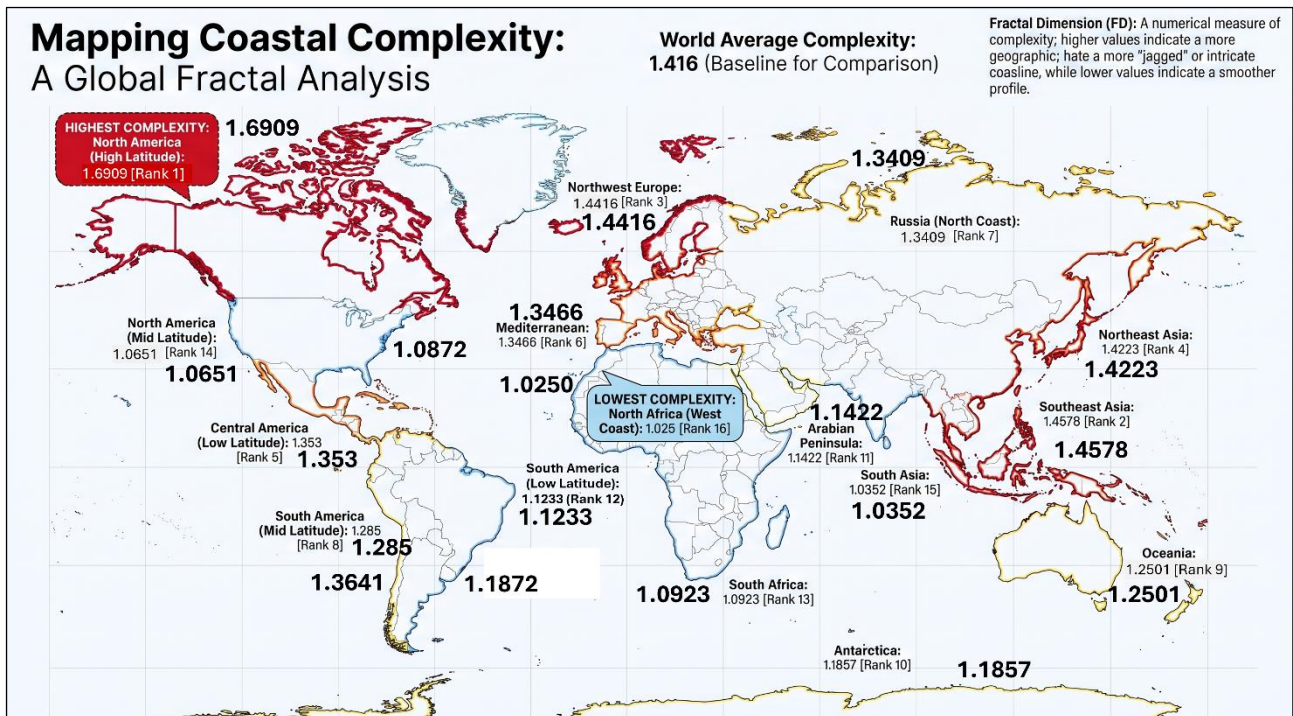


**Fig. 4 Global Geographic Distribution of Coastal Fractal Complexity.** This figure maps the global distribution of coastal complexity across 16 subdivisions. High-latitude North America exhibits the maximum global complexity ( $D_b = 1.6909$ ) due to deeply incised glacio-geomorphic fjord systems, while Northwest Europe ( $D_b = 1.4416$ ) and Southeast Asia ( $D_b = 1.4578$ ) show elevated complexities due to intense crustal deformation. Conversely, North Africa ( $D_b = 1.0250$ ) represents the lowest-ruggedness global baseline.

Our global regional assessment resolves profound disparities in coastal complexity, demonstrating a robust, first-order correlation between regional fractal dimensions and macroscopic tectonic drivers. The empirical datasets bifurcate into two statistically distinct geodynamical groups:

- Group 1: Active Convergent Margins and Orogenic Complexity Amplification.** This group encompasses regional coastlines situated along active plate boundaries, primarily dominated by convergent subduction zones and multi-plate collisional interfaces. The continuous subduction of denser oceanic lithosphere drives intense compressive stress fields, continuous crustal deformation, rapid vertical orogenic uplift, and dense fault-propagation folding. These forcing mechanisms systematically segment and shatter the terrestrial boundary, manifesting as highly rugged, fragmented, and irregular coastal profiles with prominently elevated fractal dimensions ( $D_b \gg 1.1$ ) (Keller and Pinter 2002). Southeast Asia exhibits the highest geometric complexity globally within the subglacial dataset ( $D_b = 1.4578$ ), driven by active island-arc accretion and multi-directional subduction. This is followed by Northeast Asia ( $D_b = 1.4223$ ), the Mediterranean collision interface ( $D_b = 1.3466$ ), and Oceania ( $D_b = 1.2501$ ). Similarly, the active Pacific convergent subduction margin of low-latitude South America yields  $D_b = 1.1781$ , driven by Andean orogenesis.

# Tectonic Fingerprints: How Plate Boundaries Shape Coastal Complexity

Macroscopic tectonic plate dynamics—specifically the difference between active subduction zones and stable margins—dictate the geometric complexity (Fractal Dimension) of global coastlines. Using a novel vector-based fractal methodology, researchers calculate the Box-Counting Fractal Dimension ( $D_b$ ). A value of 1.0 represents a perfectly smooth line, while values approaching 2.0 represent extreme, infinite complexity.

## Group 1: Active Subduction Zones (High Complexity)

**Intense Crustal Deformation  
Drives High Complexity**



Regions on active convergent boundaries experience massive orogenic uplift and pervasive fault networking, which systematically fractures the coastline into highly irregular shapes.



### Southeast Asia

This region exhibits the highest complexity in the subduction group due to its dense concentration of island arcs and volatile plate margins.



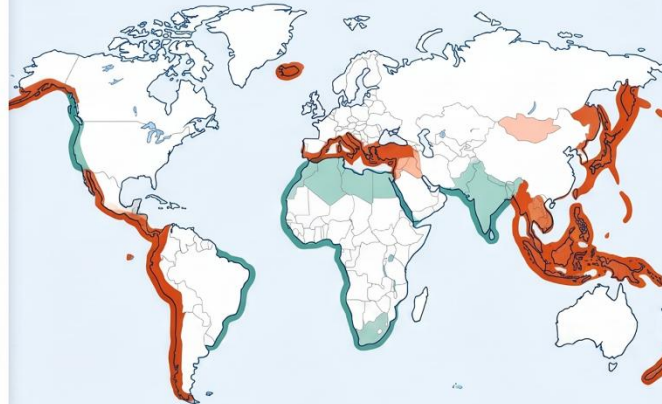
### Northeast Asia

Continued tectonic activity results in a significantly elevated fractal signature compared to the global average of 1.416.



### Low-latitude West Coast of South America

The massive orogenic uplift of the Andes directly fragments the continental boundary, creating a jagged geometry.

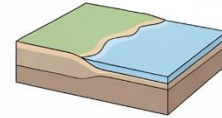


## Regional Comparison Summary

| Region                  | Tectonic Type               | Fractal Dimension ( $D_b$ ) |
|-------------------------|-----------------------------|-----------------------------|
| Southeast Asia          | Group 1 (Active Subduction) | 1.4578                      |
| Northeast Asia          | Group 1 (Active Subduction) | 1.4223                      |
| Mediterranean           | Group 1 (Active Subduction) | 1.1611                      |
| Oceania                 | Group 1 (Active Subduction) | 1.1351                      |
| South America (W Coast) | Group 1 (Active Subduction) | 1.1781                      |
| South America (E Coast) | Group 2 (Stable Margin)     | 1.0831                      |
| South Africa            | Group 2 (Stable Margin)     | 1.0923                      |
| North America (W Coast) | Group 2 (Transform/Stable)  | 1.0460                      |
| South Asia              | Group 2 (Stable Margin)     | 1.0352                      |
| North Africa (W Coast)  | Group 2 (Stable Margin)     | 1.0250                      |

## Group 2: Stable Passive Margins & Transform Boundaries (Low Complexity)

**Structural Stability Leads to  
Smooth Coastal Profiles**



Passive margins lack the severe vertical uplift and compressive fracturing inherent to subduction zones, resulting in simpler, more linear geographic profiles.

### West Coast of North America



This region represents the lowest global complexity recorded, indicating a remarkably smooth and stable tectonic history.

### South Asia

Despite its large size, the coastal margin remains relatively simple due to its stable geological positioning.



### The Transform Fault "Smoothing" Effect

The Mid-latitude West Coast of North America ( $D_b = 1.0450$ ) has a suppressed fractal dimension because its boundary is governed by horizontal transform faulting rather than vertical subduction-driven mountain building.



**Fig. 5 Tectonic Fingerprints: Coastal Complexity Comparison Between Active Subduction Zones and Stable Margins.** This schematic contrasts active convergent boundaries (Group 1, e.g., Southeast Asia, Northeast Asia) against stable passive and transform boundaries (Group 2, e.g., North Africa, South Asia), quantitatively demonstrating that tectonic compression and subduction systematically amplify fractal coastal complexity whereas strike-slip horizontal faulting and passive margin thermal subsidence structurally suppress it.

- Group 2: Structurally Suppressed and Transform Boundaries.** This category consists of stable passive continental margins governed by prolonged thermal subsidence, or regions dominated by strike-slip transform boundaries. Lacking compressive stress fields and severe vertical displacement, these coastlines are shaped by long-term subaerial weathering and wave-induced marine planation, tending toward highly linear, low-stress geomorphological baselines (Migoñ 2010). The West Coast of North Africa registers the lowest complexity within the global dataset ( $D_b = 1.0250$ ), closely aligned with stable cratonic margins in South Asia ( $D_b = 1.0352$ ) and South Africa ( $D_b = 1.0923$ ).

Notably, the Mid-latitude West Coast of North America exhibits a suppressed  $D_b$  of 1.046. Although situated along an active plate boundary, this Pacific margin is dominated by horizontal strike-slip transform tectonics (e.g., the San Andreas fault system). Lacking the compressive fracturing and severe vertical uplift characteristic of subduction zones, lateral displacement fails to generate high-frequency coastal ruggedness, presenting a smoother profile than its passive eastern counterpart ( $D_b = 1.0872$ ) (Keller and Pinter 2002). This transform-boundary scenario demonstrates that lithospheric displacement styles act as a first-order control on structural complexity (schematically conceptualized in Fig. 5). Supplementary Fig. S11 shows a detailed transcontinental comparative analysis of coastal complexity across the Americas—encompassing glaciated Patagonia, low-latitude active subduction, and the transform-suppressed western margin.

### 3.4 Co-scaling and Symmetry Analysis of Conjugate Margin Geometry via Spatial Filtering

To evaluate the multi-scale geometric symmetry and morphometric congruence of conjugate continental margins, this study implements a macro-scale spatial filter to analyze ancient rift-related geomorphological structures. Over geological timescales, superficial earth-surface processes—including wave-induced marine erosion, fluctuating sea levels, and subaerial weathering—systematically alter coastline geometries, introducing high-frequency modern noise that obscures primary tectonic boundaries (Moores and Twiss 2014). To isolate the low-frequency geometric signals deeply embedded in the continental crust, we restrict the box-counting analysis to a macro-scale spatial bandwidth ranging from Zoom 2 to Zoom 7. This operational window corresponds to physical grid edge lengths  $\epsilon$  strictly exceeding 0.8 km (evaluated at the southernmost tip of Africa with latitude  $35^\circ\text{S}$ ), effectively filtering out contemporary geomorphological overprints and localized anthropogenic modifications.

Our quantitative evaluation focuses on the conjugate margins of the South Atlantic Basin: the western coast of Africa, spanning from the Cavalla River estuary to Vredenburg, mapped against the corresponding eastern coast of South America, spanning from the Amazon River estuary to Bahía Blanca. Under the  $>0.8$  km spatial filter, the box-counting regression yields highly convergent, scale-independent fractal dimensions for both continental margins:  $D_{b,SA} = 1.0482$  (South American Margin) and  $D_{b,Af} = 1.0514$  (African Margin). The absolute dimensional difference between these two historically contiguous boundaries is exceptionally minimal:  $\Delta D_b = 0.0032$ . This translates to a negligible  $\sim 0.3\%$  relative variance, demonstrating an extraordinary degree of geometric symmetry and co-scaling behavior preserved across the South Atlantic basin. Furthermore, a joint scatter plot comparing the multi-scale occupied grid counts  $N(\epsilon)$  of South America against Africa across the Zoom 2 to Zoom 7 spectrum reveals a near-perfect linear correlation:  $R^2 = 0.9945$  (Fig. 6). This highly stable power-law alignment indicates that both margins share a highly synchronized scaling trajectory governed by their shared rifting history (Bullard et al. 1965).

To establish the statistical significance and uniqueness of this morphological alignment, high-latitude North America was utilized as a divergent control baseline. Cross-comparison regressions benchmarking North American coastal geometries against the South American and African datasets yield substantially

weaker linear correlations:  $R^2 = 0.2622$  for North America vs. South America and  $R^2 = 0.2503$  for North America vs. Africa.

These control regressions demonstrate that the high-degree geometric correlation between South America and Africa is highly unique and statistically non-coincidental. The matching, deep-seated morphometric signatures prove that low-frequency geomorphological features remain quantitatively preserved across vast geological epochs, establishing this multi-scale framework as a powerful, reproducible GIS tool for palaeogeographical reconstructions. The planetary-scale tectonic fingerprints, multi-scale symmetry scatter plots, and non-coincidental South Atlantic conjugate margin correlations are presented in Supplementary Fig. S12.

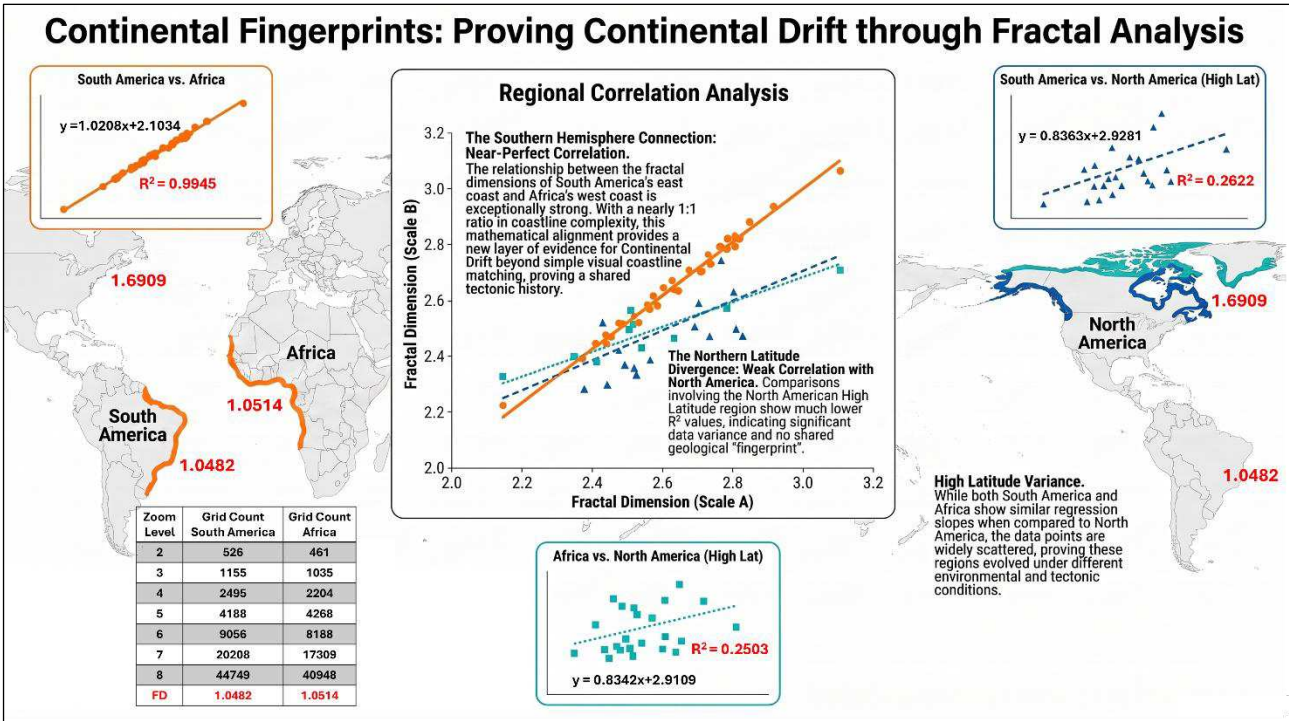


**Fig. 6 Multi-Scale Geometric Symmetry and Linear Correlation Between Conjugate Margins.** This figure demonstrates the geometric similarity and co-scaling behavior between the conjugate margins of South America and Africa using macro-scale spatial filtering ( $>0.8$  km, Zoom 2 to 7). The box-counting method yields exceptionally close fractal dimensions (1.0482 for South America and 1.0514 for Africa), representing a minimal difference of only 0.0032 ( $\sim 0.3\%$  relative variance). A scatter plot comparing their multi-scale grid counts reveals a near-perfect linear correlation ( $R^2 = 0.9945$ ), proving their high-degree scaling symmetry. Control comparisons using North America as a divergent baseline yield weak correlations ( $R^2 \sim 0.25$ ), mathematically confirming that this South Atlantic alignment is highly unique and statistically non-coincidental.

## 4. Discussion

### 4.1 Methodological Rigor and the Web-API Rendering Paradox

The core technical advancement of the proposed geospatial informatics pipeline lies in its ability to resolve the historical trade-off between scale range and operator subjectivity in multi-scale box-counting

fractal analyses (Mandelbrot 1967, 1982). Conventional approaches have traditionally superimposed dynamic grids on static, resolution-limited raster images, resulting in severe quantization artifacts and loss of geometric fidelity at high magnification levels (Plantin 2018). By reversing this dynamic—maintaining a static pixel-size measuring grid while programmatically scaling the underlying map vector geometries through commercial Web-mapping APIs—the pipeline achieves a continuous multi-scale characterization from macro-geography ( $\sim 1,000$  km) to micro-structures ( $\sim 50$  m). However, this dynamic scaling approach introduces an inherent technical paradox: while the Web-mapping API renders geometries on the fly using underlying vector databases, the computational environment must capture these elements onto high-resolution rasterized canvases for subsequent digital image processing. Thus, our pipeline is properly classified as a hybrid vector-rendering and raster-processing computational framework.

This hybrid nature necessitates a rigorous discussion of cartographic generalization and parameter sensitivity, which have historically been underreported in commercial API-based spatial models. Commercial mapping APIs (such as Google Maps) employ proprietary, scale-dependent generalization algorithms—including Douglas-Peucker line simplification, feature selection, and local projection adjustments—to optimize visual rendering at different zoom levels (Goodchild 1980). Consequently, the coastline geometry displayed at Zoom level  $n$  is not a mathematically identical scaling of Zoom  $n - 1$ , but a simplified, cartographically curated representation. The fractal dimension  $D_b$  extracted by our algorithm is therefore a quantitative index of the 'cartographic complexity' of the digitized geospatial database, rather than an absolute, scale-invariant physical coastline. Furthermore, the extracted  $D_b$  is highly sensitive to the parameters of the digital image processing step, particularly the hysteresis thresholds of the Canny edge detector and the binarization segmentation thresholds. In our MATLAB implementation, these parameters were held constant across all zoom levels to eliminate intra-analysis variance, but future informatics studies should incorporate systematic sensitivity analyses to quantify the exact mathematical influence of edge-thresholding parameters on global geomorphological classification.

## 4.2 Geomorphological Scale Sensitivity and Anthropogenic Inflation

A compelling verification of the pipeline's scale-resolving capability is demonstrated by the biphasic scaling behavior observed along the Norwegian coastline. Traditional single-scale analyses often yield a static  $D_b$  that obscures local scaling transitions. In contrast, our dynamic framework captures a distinct 'dip' in the localized fractal dimension  $D_b(n)$  at intermediate spatial scales, followed by a robust geometric recovery. This biphasic pattern represents a physical geomorphological transition from macro-scale tectonic fjords to micro-scale islands and 'fjards' (glaciated lowlands). At meso-scales (4 km to 500 m, corresponding to Zoom levels 4 to 7), the coastline's geometric complexity is dominated by deep, parallel glacial valleys whose width-to-depth ratios are physically bounded by ancient glacial erosion patterns. This produces a highly rugged, self-similar geometry with a peak  $D_b$  of 1.5167, aligning precisely with the classic fractal models of Jens Feder (Feder 1988). At micro-scales (below 500 m), the measuring grid penetrates the interior of these glacial troughs, where the steep, near-linear granite cliffs present simplified, Euclidean profiles that cause a temporary drop in  $D_b(n)$ . This geometric 'suppression' is only broken at high magnifications (Zoom levels 8 to 11), where the algorithm begins resolving the

complex, low-relief island systems and skerry guards (fjards) typical of post-glacial shorelines, triggering a second phase of fractal complexity.

Conversely, our analysis of the Taiwanese coastline highlights a critical phenomenon of 'artificial scaling inflation' in modern GIS datasets. At macro-to-meso scales, Taiwan exhibits a moderately smooth geomorphic baseline. However, at micro-spatial scales (Zoom levels 14 to 17, corresponding to physical grid sizes under 10 m), the localized  $D_b$  experiences an anomalous, steep upward trajectory, peaking at 1.1713. While a purely mathematical interpretation might attribute this to high-frequency natural ruggedness, geomorphological ground-truthing reveals this as an artifact of extensive anthropogenic modifications. Currently, approximately 56.29% of Taiwan's coastline is heavily artificialized with harbors, dykes, and massive concrete tetrapods designed for coastal defense. At sub-10 m resolutions, the high-contrast, tessellated geometries of these concrete arrays are successfully resolved by the Canny detector as highly dense, multi-directional edge fragments. This artificial complexity inflates the box-counting occupancy  $N(\epsilon)$ , resulting in an artificially elevated  $D_b$ . This finding demonstrates that high-resolution geospatial informatics pipelines must incorporate land-use and anthropogenic filters to prevent artificial structures from confounding natural geomorphological complexity metrics.

### 4.3 Macroscopic Tectonic Taxonomy and the Transform Suppression Paradox

By compiling a systematic, quantitative taxonomy across 16 diverse global regions, this study establishes a robust statistical association between macroscopic plate boundary regimes and coastal fractal complexity. Active convergent boundaries, such as the active subduction zones of Southeast Asia ( $D_b = 1.4578$ ) and Northeast Asia ( $D_b = 1.4223$ ), consistently exhibit the highest fractal dimensions globally, second only to glaciated fjord systems. The intense compressive stress, vertical orogenesis, volcanism, and rapid tectonic uplift characteristic of convergent margins continuously generate high-frequency coastal fragmentation, multiple offshore barrier islands, and complex embayments. In stark contrast, stable passive margins, such as the Atlantic coast of North Africa ( $D_b = 1.0250$ ) and South Asia ( $D_b = 1.0352$ ), exhibit extremely low, near-Euclidean fractal dimensions. These stable, sediment-rich margins are dominated by long-term deltaic deposition, wave-action smoothing, and coastal progradation, which systematically suppress high-frequency geometric irregularities.

Intriguingly, our global taxonomy uncovers what we define as the 'Transform Suppression Paradox' along strike-slip plate boundaries. The Pacific coast of the United States (US West Coast), which is dominated by the San Andreas active transform fault system, exhibits a remarkably low fractal dimension ( $D_b = 1.0460$ ). From a conventional geomorphic perspective, active tectonic margins are expected to display high complexity. However, the strike-slip motion along transform faults is predominantly horizontal, resulting in lateral displacement with minimal vertical crustal deformation or folding. This strike-slip kinematic regime produces highly linear, parallel coastal ranges and straight, fault-controlled shorelines with virtually no major embayments or complex island systems. Consequently, despite being an active plate margin, its fractal complexity is severely suppressed, presenting a profile that is smoother than even the stable passive margin of the US East Coast ( $D_b = 1.0872$ ), which is characterized by extensive barrier islands and estuary systems. This paradox underscores the necessity of utilizing multi-scale spatial informatics to differentiate between compressive (vertical) and shear (horizontal) tectonic forces in geomorphological modeling.

#### 4.4 Conjugate Margins: Scaling Symmetry vs. the Continental Drift Fallacy

A critical area of debate in multi-scale geomorphic scaling is the morphotectonic symmetry of conjugate continental margins. In our study, a double-logarithmic regression applied to the South American and African coastlines yields an exceptionally high linear correlation ( $R^2 = 0.9945$ ) across multiple zoom levels. While simplistic interpretations of this data might argue that this near-perfect correlation directly proves Alfred Wegener's continental drift theory (Wegener 1912), we must rigorously address the statistical limitations of this assertion. In multi-scale nested datasets, a high  $R^2$  in double-logarithmic box-counting is an inherent mathematical consequence of the nested spatial structure; as the physical scale ( $\epsilon$ ) decreases, the cumulative grid count  $N(\epsilon)$  must inherently increase exponentially in both systems. Therefore, a high correlation coefficient alone does not validate geometric jigsaw-puzzle complementarity or a direct physical fit, but rather indicates a shared scaling behavior or congruent scaling symmetry over the investigated spatial spectrum.

To resolve this limitation and isolate the true paleogeographic signal, our pipeline implements a macro-scale spatial filter ( $> 0.8$  km, corresponding to Zoom levels 2 to 7) to suppress contemporary, high-frequency geomorphological noise. While modern wave erosion, coastal deposition, and anthropogenic modifications have heavily altered the micro-scale structures of both continents over 140 million years of separation, the macro-scale basement structures are governed by the deep crustal geometry of the original rifting process. By filtering out the high-frequency noise, the absolute fractal dimensions of the conjugate margins—South America ( $D_b = 1.0482$ ) and West Africa ( $D_b = 1.0514$ )—reveal an exceptionally tight geometric coupling, with an absolute difference of only  $\Delta D_b = 0.0032$  ( $\sim 0.3\%$  relative variation). In contrast, cross-comparison with the non-conjugate North American baseline yields a weak, non-congruent relationship ( $R^2 \approx 0.25$  under identical filtering). This exceptionally tight scaling symmetry represents a persistent paleogeographic and structural legacy of the Gondwana break-up, demonstrating that macro-scale fractal metrics can serve as powerful, quantitative exploratory indices to support plate tectonic reconstructions and validate deep-time geodynamic models.

#### 4.5 Software Portability, Open Science, and Future Directions

In alignment with the core mission of modern geospatial informatics, a major contribution of this study is the development of a highly portable, open-source computational pipeline that democratizes advanced fractal analysis for the broader scientific community. By utilizing standard, widely documented Web APIs and providing the complete implementation in MATLAB, we ensure that other earth scientists can easily reproduce and extend our findings without requiring expensive, proprietary GIS software. A key technical breakthrough in our open-source workflow is the documentation of Gecko-engine (Mozilla Firefox) compatibility for map-tile acquisition. We discovered that WebKit-based engines (e.g., Google Chrome, Apple Safari) introduce artificial single-pixel grid lines at tile boundaries during dynamic programmatic zoom rendering, which trigger severe false positives during MATLAB Canny edge detection. Documenting and resolving this Gecko-specific rendering advantage represents a highly practical informatics contribution that ensures high data quality for future Web-API-based geomorphic models.

Despite its robustness, the current pipeline has several limitations that define exciting avenues for future informatics research. First, the framework is currently restricted to 2D coastline geometries; integrating 3D digital elevation models (DEMs) via Google Earth 3D API could allow the pipeline to extract 3D fractal surfaces, providing deeper insights into rugged mountain terrains and volcanic structures. Second, the reliance on a single commercial Web-mapping API introduces data-dependency risks; future iterations should incorporate multi-source API integration (e.g., OpenStreetMap, Mapbox, and USGS databases) to evaluate cartographic generalization discrepancies across different spatial platforms. Finally, combining our automated fractal pipeline with machine learning classifiers (such as Random Forests or Support Vector Machines) could enable fully automated, multi-parameter geomorphological classification of global coastlines, paving the way for next-generation, AI-driven digital earth systems.

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