

1 **TWO TYPES OF INVERSELY GRADED BANDS IN**
2 **SPACED STRATIFICATION IDENTIFIED BY**
3 **MICROTEXTURAL ANALYSIS USING A CONVOLUTIONAL**
4 **NEURAL NETWORK**

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12 Running title: TWO TYPES OF BANDS IN SPACED STRATIFICATION
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ABSTRACT

Spaced stratification is a sedimentary structure consisting of multiple inversely graded bands, traditionally interpreted as traction-carpet deposits formed under high-concentration sediment gravity flows. Although widely reported from coarse-grained sandstones deposited by deep-sea turbidity currents, pyroclastic density currents, and hyperconcentrated flows, its formation mechanism remains controversial. Competing hypotheses—ranging from freezing of traction carpets to bedform migration and turbulent sweep-fallout cycles—have lacked quantitative validation from natural deposits. To address this, we conducted a microtextural analysis of spaced stratification in ancient turbidites to clarify its internal variability and depositional implications. We analyzed coarse-grained sandstone samples from the Upper Cretaceous Izumi Group (southwest Japan) using a convolutional-neural-network (CNN)-based semantic segmentation model. The model automatically distinguished grains from the matrix in cross-sectional images with 78.7% accuracy at a resolution of 5 μm per pixel, enabling high-throughput quantification of grain size and orientation. Multivariate analyses of the measured grain data revealed two distinct types of inversely graded bands: (1) Type A, characterized by coarser mean grain size, bimodal distributions of imbrication angles, and pronounced internal variability; and (2) Type B, composed of finer grains with unimodal, upstream-dipping imbrication and more uniform textures. These results demonstrate that deposits previously grouped under spaced stratification actually encompass at least two microstructurally distinct types that are likely formed through different depositional dynamics. The CNN-based image analysis provides a new methodological framework for objective, quantitative characterization of sedimentary microtextures at high spatial resolution. Further experimental and numerical studies replicating these two types of banded structures under controlled flow conditions will be essential to constrain their formation processes and refine paleoenvironmental interpretations of high-concentration deposits of sediment gravity flows.

INTRODUCTION

Spaced stratification, also referred to as a traction carpet-deposit, is a sedimentary structure observed in coarse-grained sandstones. This sedimentary structure was recognized by Hiscott and Middleton (1979) as stratified layers in coarse sandstone beds and was later named spaced stratification by Hiscott (1994). It is characterized by the repetition of inversely graded bands, each several to ten centimeters thick, within a single sandstone bed. Hiscott and Middleton (1979, 1980) and Hiscott (1994) described its distinctive features as follows: (1) each band ranges from a few centimeters to about 10 cm in thickness; (2) each band is overlain by a horizontal or sub-horizontal erosional surface; (3) the interval from the base to about 1 cm above the basal erosional surface shows inverse grading, overlain by a homogeneous massive sand interval; (4) the long axes of sand grains are aligned parallel to the flow and imbricate upcurrent at about 20–40°, producing an a(p)a(i) fabric; and (5) the maximum grain size tends to become finer in the upper bands, while the band thickness generally decreases upward. Note that in the a(p)a(i) fabric the grain axis is parallel to the flow direction and imbricate. In summary, spaced stratification has an overall fining- and thinning-upward trend.

Spaced stratification has been reported from deposits generated by a variety of sedimentary processes. It was first identified in turbidites by Hiscott and Middleton (1979, 1980), who emphasized its occurrence in thick-bedded sandstones deposited from high-density turbidity currents. Later studies recognized spaced stratification in hyperconcentrated flow deposits in fluvial settings (Benvenuti and Martini 2002; Masuda et al. 2005), as well as deposits of pyroclastic density currents (Palladino and Simei 2002; Sohn et al. 2005; Branney and Kokelaar 2002). The recurrence of this structure across marine, fluvial, and volcanic depositional settings underscores its significance for understanding the dynamics of high-density gravity flows. Clarifying the processes responsible for its formation not only advances our fundamental

knowledge of sediment-transport mechanisms but also provides critical insights into predicting hazardous sediment gravity flows in both terrestrial and submarine environments.

Traction carpets—often referred to as sheet flows—have long been regarded as the principal mechanism responsible for spaced stratification (Hiscott and Middleton 1980; Lowe 1982; Sohn 1997). A traction carpet is a thin, near-bed layer of sand that moves en masse under intense shear, with grains in sustained contact and undergoing frequent collisions (Hanes and Bowen 1985). In this state, dispersive (collision) stresses and frictional contacts within the granular layer carry most of the shear stress, while the overlying fluid remains turbulent and provides momentum (Bagnold 1956; Hanes and Bowen 1985). Typically, traction carpets are only a few to ten grain diameters thick and have a convex-up velocity profile with a frictional basal zone grading upward into a more collisional regime (Lowe 1982; Jenkins and Hanes 1998). Such conditions arise at very high transport stages and have been documented in diverse environments, including catastrophic floods in rivers, high-density turbidity currents, and pyroclastic density currents (Dzulynski 1962; Sohn 1997; Branney and Kokelaar 2002).

Recent advances in laboratory experiments, numerical modeling, and field monitoring have greatly improved our understanding of traction-carpet dynamics. Flume studies have directly observed such layers, showing that their development suppresses turbulence while greatly enhancing transport capacity (Sumer et al. 1996; Dohmen-Janssen et al. 2001). DEM-CFD (discrete element method-computational fluid dynamics) simulations further reveal grain-scale kinematics, bridging Bagnold’s early physical models with modern continuum approaches (Hsu et al. 2004; Maurin et al. 2016). In addition, direct monitoring of turbidity currents in submarine canyons has confirmed the presence of dense basal layers consistent with traction-carpet models (Talling et al. 2013; Paull et al. 2018). Together, these findings demonstrate that sheet flow is a key transport regime in high-concentration sediment gravity flows.

The formation mechanism of spaced stratification was originally attributed to traction carpets (Dzulynski 1962; Hiscott and Middleton 1979, 1980). Lowe (1982) further developed this view by incorporating traction carpets into his depositional model for high-density turbidity currents. He regarded them as flow-shear-driven analogues of grain flows, distinct from gravity-driven debris flows. In his model, traction carpets were thought to undergo repeated “freezing” as the thickness of the overlying plug flow increased because of suspension fallout. Spaced stratification was thus interpreted as the product of autocyclic freezing of traction carpets, with each inversely graded band representing a frozen layer formed under dispersive pressure (Bagnold 1954).

However, this hypothesis lacks strong theoretical or empirical support. Hiscott (1994) argued that traction carpets cannot freeze in the manner proposed by Lowe (1982) because their flow structure differs fundamentally from that of debris flows with plug layers. Traction carpets are maintained by bed shear stress, which is highest near their upper boundary; therefore, the low-stress conditions required for plug development do not occur. In addition, experimental studies have shown that traction carpets are only several to ten grain diameters thick—about 1 cm in coarse sands—making them too thin to account for the 10-cm-thick inversely graded bands observed in spaced stratification. Indeed, recent experiments simulating sediment transport by traction carpets have not reproduced spaced stratification. Instead, Hernandez-Moreira et al. (2020) reported that traction carpet deposits tend to become structureless.

Although not confirmed directly, several mechanisms linking traction carpets and spaced stratification have been proposed. Hiscott (1994) proposed the sweep-fallout model, in which traction carpets are only the lowermost part of a band. In this model, instantaneous increases in shear stress generate a thin traction carpet, while subsequent deceleration triggers rapid suspension fallout, producing the overlying massive interval. Repetition of this process, driven by turbulent burst–sweep cycles, accounts for the banded architecture. Sohn (1997) offered another variation. On the basis of theoretical considerations and experimental results, he proposed a two-layer

structure consisting of a basal frictional region with grain concentrations exceeding 80% and an overlying collisional region of 15–80%. Unlike in Lowe’s model, deposition occurs not by freezing but through progressive accumulation. A filtering mechanism—kinematic sieving in the collisional zone—was invoked to preferentially transfer fine grains downward, while coarse grains remained longer in the moving layer, delaying their deposition and forming inverse grading. Sohn (1997) also related the stacking of multiple bands to periodic velocity fluctuations, although he attributed these to larger-scale turbulent structures rather than small-scale burst–sweep cycles.

As an alternative to traction-carpet models, several studies have suggested that bedform migration may account for the origin of spaced stratification. Best (1992) interpreted the migration of low-amplitude bedforms as producing nearly bedding-parallel surfaces overlain by inversely graded bands. Miyata and Tanaka (2011) conducted flume experiments on stable upstream-migrating antidunes and showed that inversely graded bands may result from preferential accumulation of fine grains in troughs, whereas coarser grains tend to concentrate at crests. As an antidune migrates upstream, its trough erodes the lee side of the preceding bedform, thereby generating an erosional surface and depositing an overlying inversely graded band.

A detailed characterization of the microtextures in spaced stratification is essential for evaluating competing hypotheses of its origin. Although experimental studies have provided important analogues, our study focuses on actual deposits, where high-resolution analyses of grain size and fabric offer a direct means of identifying diagnostic features of sedimentary structures. Grain size is a key factor controlling the development of bedforms under open-channel and oscillatory flows (e.g., Ohata et al. 2017), while grain fabric provides valuable information for reconstructing flow conditions (Rees 1968; Taira 1989; Yokokawa 1998). Previous work has shown that deposits often have characteristic patterns of imbrication angles or preferred grain orientations depending on the type of formative bedform. For example, Yagishita and Taira (1989) demonstrated that antidune deposits in ancient successions preserve fabric features similar

to those produced in flume experiments, and Naruse and Masuda (2006) illustrated how fabric analysis can reveal structures in debris-flow deposits that are otherwise invisible to visual inspection. By systematically documenting such grain-scale attributes in natural examples of spaced stratification, this study provides a foundation for evaluating which formation mechanisms are plausible. In this way, the characterization of real deposits establishes a necessary empirical basis for guiding future experimental investigations more effectively.

Previous studies of spaced stratification have examined grain fabric and grain size mainly at the thin-section scale (Hiscott and Middleton 1980; Yagishita and Taira 1989). However, given that spaced stratification typically extends over several tens of centimeters to meters, such limited observation windows may not adequately capture their overall characteristics. For example, Hiscott and Middleton (1980) analyzed sandstone samples processed into 2.5 cm across, selected from intervals with pronounced vertical grain-size variation, and traced grain outlines to calculate mean imbrication angles and grain sizes. Similarly, Yagishita (1994) measured imbrication angles from thin sections prepared from coarse-grained parts of spaced stratification. While these studies provide useful grain-scale information, their observations are confined to small, localized regions and therefore fail to capture textural trends at the scale of the sedimentary structure. Therefore, a new approach is needed to capture grain-scale data more efficiently and at scales commensurate with the full dimensions of spaced stratification.

Combining image analysis with convolutional-neural-network (CNN)-based semantic segmentation offers a promising solution to these limitations, enabling rapid and high-precision measurements across large areas. High-resolution images can now be obtained easily, even with desktop scanners, and recent advances in image-processing techniques enable CNN-based models to classify pixels at the grain scale. CNN models are widely used for object recognition, while semantic segmentation assigns each pixel to a specific class, providing detailed and quantitative image interpretation (Long et al. 2015; Ronneberger et al. 2015). Applications of CNN-based

segmentation are rapidly expanding in sedimentology: for instance, Chen et al. (2020) distinguished mineral particles and clay aggregates in SEM images; Kikuchi and Naruse (2024) identified trace fossils in core and outcrop images to quantify bioturbation intensity; and Okuda et al. (2024) analyzed grain-size distributions in scanned sandstone images showing parallel lamination. These examples demonstrate that CNN-based image analysis has already proven effective at the microscale and strongly suggest its potential for characterizing the grain fabrics of spaced stratification.

Earlier approaches to automated grain detection can be broadly classified into two categories: (1) binarization on the basis of color differences between grains and matrix (Francus 1998; Naruse and Masuda 2006), and (2) contour extraction from image gradients (Canny 1986; Starkey and Samantaray 1993). While effective for specific image types, these methods require extensive parameter tuning and often fail when applied to new datasets. In contrast, CNN-based methods, including the ResUNet model used here, can be retrained relatively easily compared to conventional methods that require extensive manual parameter tuning to match the characteristics of new images, thereby offering far greater flexibility and scalability.

In this study, we investigated the formation processes of spaced stratification through quantitative analysis of microtextures. We applied a CNN-based semantic segmentation model to scanned cross-sectional images of the samples to acquire more grain-scale data from a broader range than previous methods. Samples were collected from the submarine-fan deposits in the Bandodani and Nada formations of the Upper Cretaceous Izumi Group in southwest Japan (Ichikawa et al. 1979; Tanaka 1989; Shimamura 1989; Kikuchi and Kotake 2013). The collected samples were cut, polished, and scanned with a desktop scanner to obtain high-resolution cross-sectional images, which were then analyzed using a CNN model trained to distinguish grains from matrix. By applying this method to cross sections, we were able to observe microtextures at the micrometer scale and efficiently measure thousands of grains. This approach thus enabled

unprecedented integration of grain-scale observations with bed-scale structures, achieving an analytical scale that has been unattainable with conventional thin-section methods. This study establishes a framework for providing a new empirical basis for testing formation models of spaced stratification, rather than focusing solely on methodological development.

GEOLOGIC SETTINGS

The Upper Cretaceous Izumi Group is distributed across Shikoku Island and the Kii Peninsula along the northern side of the Median Tectonic Line (MTL) in southwest Japan (Fig. 1A, B). The Izumi Group is characterized mainly by alternating beds of sandstone, mudstone, and conglomerate. It extends approximately 300 km in the east–west direction with a width of more than 10 km (Yamasaki 1986). The Group unconformably overlies the Ryoke granites at its northern margin, while its southern part is adjacent to the Sambagawa Metamorphic Belt across the MTL (Ichikawa et al. 1979; Miyata 1990). Bedding in the Izumi Group generally strikes northeast–southwest and dips to the southeast (Tanaka et al. 1952; Tanaka 1989; Noda and Toshimitsu 2009). The depositional age of the Group has been estimated as late Campanian to early Maastrichtian, on the basis of biostratigraphic correlations using foraminifer, radiolarian, and ammonite fossils (Sasai 1936; Morozumi 1985; Yamasaki 1986, 1987), as well as magnetostratigraphy (Kodama 1990). It has also been reported that the deposition of the Izumi Group progressed from west to east (Suyari 1973; Morozumi 1985).

The tectonic setting of the Izumi Group basin has long been debated. Several studies have suggested that the Izumi Group was deposited in a pull-apart basin associated with a large-scale sinistral strike-slip fault zone extending east–west, on the basis of variations in depositional age, structural features, and paleocurrent directions (i.e., the MTL) (Ichikawa et al. 1981; Taira et al. 1983; Yamasaki 1986; Miyata 1990; Kikuchi and Kotake 2013). Ichikawa et al. (1981); Tanaka (1989) proposed that the pull-apart basin migrated eastward in a stepwise manner by about 10–15 km, as inferred from cyclic vertical and lateral changes in lithofacies. In contrast,

Yamakita and Ito (1999) suggested a continuous eastward migration of the basin on the basis of numerical experiments, attributing cyclic changes in the succession to switching of sediment-supply systems rather than discontinuous subsidence. More recently, however, Nakano et al. (2021) argued that the Izumi Group represents forearc basin deposits rather than a pull-apart basin, on the basis of its wide distribution and discrepancies between the estimated active period of the MTL and the depositional ages.

Based on lithofacies and structural characteristics, the Izumi Group is classified into three facies: the Northern Marginal, Main, and Southern Facies (Tanaka et al. 1952; Ichikawa et al. 1979; Morozumi 1985; Hashizume et al. 1993; Noda and Toshimitsu 2009). The Main Facies forms the principal basin fill and consists of thick pebbly sandstones, fine sandstones, and mudstones, interpreted as deposits of a turbidite system (Tanaka 1989). The Northern Marginal Facies is present along the northern margin of the basin and is composed of thick conglomerates and mudstones deposited in a shallow-marine environment (Morozumi 1985). The Southern Facies is discontinuously distributed along the southern margin of the basin and contains thick conglomerates, sandstones, and mudstones, which are also interpreted as shallow-marine deposits (Tanaka 1965; Hashizume et al. 1993).

This study investigates turbidites of the Bandodani Formation, distributed on Ogejima Island north of Naruto City, Tokushima Prefecture. The Bandodani Formation corresponds to the middle part of the Main Facies of the Izumi Group (Morozumi 1985; Kikuchi and Kotake 2013). It extends over an area 10 km wide and 13 km long (Fig. 1C) and is more than 6,000 m thick (Yamasaki 1986). On Ogejima Island, the Bandodani Formation is composed mainly of alternating beds of sandstone and mudstone, with intercalated pebbly sandstone beds (Kikuchi and Kotake 2013; Kikuchi 2015). Sandstone-dominated and mudstone-dominated successions are stacked repeatedly in 10–100 m cycles (Kikuchi 2015). In the study area, the Bandodani

Formation strikes N 40° E–N 60° E and dips 30° S–80° S, showing a homoclinic structure (Kikuchi and Kotake 2013; Kikuchi 2015).

We also examined turbidites of the Nada Formation, distributed in the southeastern part of Awaji Island, Hyogo Prefecture (Fig. 1D). The Nada Formation extends over an area 5 km wide and 8 km long (Goto and Miyata 1982) and has a total thickness of more than 1,100 m (Tanaka et al. 1952), well exposed along coastal cliffs. The study area consists of alternating thick-bedded coarse sandstones and conglomerates with thin intercalations of mudstone (Sasai 1936; Shimamura 1989). The Nada Formation strikes N 20° E–N 50° E and dips 40° S–60° S.

MATERIALS AND METHODS

In this study, we observe and analyze the microtextures of bands that constitute spaced stratification in order to constrain their depositional processes. First, high-resolution cross-sectional images of collected samples were obtained using a flatbed scanner. Second, the scanned images were analyzed using a CNN-based image-analysis model to quantify sediment texture (grain size and fabric). Descriptive statistics of sediment texture were then calculated from the measured-grain datasets. Finally, cluster analysis of the statistical results was conducted to evaluate the diversity of bands in terms of textural features. The detailed procedures are described below.

Sample Preparation and Image Scanning

We collected a specimen from one sandstone bed with spaced stratification occurring in alternating thin sandstone–mudstone beds (Facies I) of the Bandodani Formation (Fig. 2A). The bed is approximately 20 cm thick and has spaced stratification composed of five bands, each up to 4 cm in thickness (Fig. 3A). Parallel lamination was also observed above the spaced stratification.

Sandstone blocks with spaced stratification were also sampled from six beds in the coarse sandstone- and conglomerate-dominated successions (Facies II) of the Nada Formation (Fig. 2B).

These beds ranged from 15 to 70 cm in thickness and contained two to five bands of spaced stratification, each 10 to 16 cm thick (Fig. 3B, and figures shown in the Supplemental Material). Parallel lamination was overlying two of the samples.

Samples were cut and polished to obtain bedding-parallel sections. The cut surfaces were impregnated with epoxy resin to prevent loss of sand grains during preparation. The polished sections were scanned using a flatbed scanner (EPSON GT-X700) at a resolution of 4,800 dpi, and grain regions in the scanned images were automatically extracted using CNN-based image-analysis techniques (described below).

The mean orientation angles of grain long axes were then calculated to estimate the paleocurrent directions of each bed. These estimates were verified against the orientations of flute casts and groove casts observed at the bases of turbidites in the study area.

The horizontal cross sections were analyzed for six of the seven bands. As a result, they all had a(p)a(i) fabrics with the preferred orientations parallel to the paleocurrents estimated from the sole casts. For confirmation, we analyzed vertical sections perpendicular to the preferred orientation direction of the horizontal sections in two of these samples; none exhibited preferred imbrication angles.

Vertical sections were then cut parallel to the paleocurrent directions. These sections were polished and scanned using the same flatbed scanner at a resolution of 4,800 dpi.

The CNN-based Image Segmentation Model

To extract sand grains from the scanned cross-sectional images, we used a convolutional-neural-network (CNN)-based semantic segmentation technique. We trained a ResUNet model (Shang et al. 2021), an extension of the U-Net architecture (Ronneberger et al. 2015) that incorporates residual connections (He et al. 2016), to classify each pixel in scanned images as either sand grain or matrix (Fig. 4).

The model was trained on datasets of high-resolution scanned images and manually traced paired images of the grain region (Fig. 5) prepared from polished sandstone samples. Training datasets included samples collected in this study and images from Okuda et al. (2024), which were obtained from turbidite sandstones of the Upper Cretaceous Izumi and Himenoura groups. The trained model was validated on independent datasets during training and evaluated on the basis of its performance in predicting grain and matrix regions.

The performance of the trained model was assessed by calculating the root-mean-squared errors (RMSEs) between predicted and ground-truth values for the area-weighted mean grain size and the mean orientation of grain long axes. The image-measurement procedures are described in the following section, and the detailed options for training and validating the CNN model are stated in the Supplemental Materials.

Measurement of Sand Grains

All grains in the binarized cross-sectional images of sandstones with spaced stratification were measured for size and long-axis orientation. In these images, grains and matrix were represented in black and white, respectively.

Prior to measurement, unnecessary areas in the images, such as resin-filled cracks, were manually removed by filling those regions with white color. Subsequently, an opening operation (erosion followed by dilation) with a 7-pixel kernel was applied to the binarized images (Soille 1999). This process reduced noise and separated distinct grains that were in contact with each other. Grains with an area of 100 pixels or less (approximately 0.0025 mm²), corresponding to silt-size particles, were excluded to minimize errors caused by image resolution.

After preprocessing, the area and shape statistics of ellipses fitted to grain contours were measured to quantitatively characterize the texture of bands constituting spaced stratification. Ellipses were fitted using a least-squares algorithm (Fitzgibbon et al. 1999). The following statistics were obtained for each grain: (a) area of the grain (A), (b) diameter of the grain area (L) (the

diameter of a circle with the same area as the grain), (c) centroid coordinates of the fitted ellipse, (d) aspect ratio of the major and minor axes, and (e) the orientation angle (θ) of the long axis with respect to the horizontal. All measurements were performed using the Python package OpenCV 4.6.0 (Bradski 2000).

Statistics Characterizing Sediment Texture for Each Interval

To evaluate spatial variations in the sediment texture of spaced stratification, descriptive statistics were calculated for each vertical interval in the sections. For every 4 mm interval, the following statistics were computed in both vertical and lateral directions: (A) the area-weighted mean grain size $\bar{D}_{\text{interval}}$, (B) the area-weighted standard deviation of grain size σ_{interval} , (C) the mean angle of grain long axes $\bar{\theta}_{\text{interval}}$, and (D) the mean resultant length $\bar{R}_{\text{interval}}$ (vector concentration).

The area-weighted mean grain size $\bar{D}$ and the standard deviation σ were calculated as:

$$\bar{D} = \frac{\sum_{i=1}^n L_i A_i}{\sum_{i=1}^n A_i}, \quad (1)$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^n (L_i - \bar{L})^2 A_i}{\sum_{i=1}^n A_i}} \quad (2)$$

where n is the number of grains, and L_i and A_i are the diameter and area of the i -th grain, respectively.

(C) The mean angle of grain long axes was calculated from the approximate ellipses to the grains. Grains with an aspect ratio of less than 1.5 were excluded. The mean angle $\bar{\theta}$ is defined as (Arai 2011):

$$\bar{\theta} = \frac{1}{2} \tan^{-1} \left(\frac{\frac{1}{n} \sum_{i=1}^n \sin 2\theta_i}{\frac{1}{n} \sum_{i=1}^n \cos 2\theta_i} \right), \quad (3)$$

where n is the number of grains and θ_i is the angle of the long axis of the i -th grain. Angles were measured from the right side of the image; in vertical sections, this corresponds to the upstream direction. Thus, positive values indicate upstream-inclined imbrications.

(D) The mean resultant length $\bar{R}$ was also computed for grains with aspect ratios greater than 1.5:

$$\bar{R} = \sqrt{\frac{\left(\sum_{i=1}^n \cos 2\theta_i \right)^2 + \left(\sum_{i=1}^n \sin 2\theta_i \right)^2}{n^2}}. \quad (4)$$

This metric ranges between 0 and 1, with higher values indicating a stronger preferred orientation of grain long axes.

To assess statistical robustness, the bootstrap method was applied to estimate 95th percentiles of statistics A–D (Efron 1981). The original grain dataset was resampled 1,000 times, and the bootstrap mean value and 95th percentile were calculated.

For distributions of grain size and orientation, additional statistical tests were performed. The Dip Test (Hartigan and Hartigan 1985) was used to measure the unimodality of grain-size distributions. For orientation data, the Rayleigh Test (Rayleigh 1880) assessed whether the data provided enough evidence to conclude that imbrication angles were nonuniformly distributed. When the null hypothesis of randomness was rejected, Watson's U^2 Test (Watson 1961; Mardia and Jupp 2000) was applied to determine if the data were sufficient to reject the null hypothesis of a single von Mises distribution. The statistical tests were performed at the significance level of 5%.

When the null hypothesis of unimodality was rejected through the Dip Test or Watson's U^2 Test, the number of modes was determined from the shapes of grain-size histograms or rose diagrams.

In such cases, mixture models were fitted: Gaussian mixtures for grain-size distributions and von Mises mixtures for orientation distributions. For each component, the mean value and mixing ratio were estimated.

Visualization of Sedimentary Structures by Textural Mapping

To visualize the spatial distribution of grain data collected over large images using the CNN model, we used a two-dimensional (2D) sediment textural mapping technique following Naruse and Masuda (2006) and Yokokawa and Naruse (2007). Maps of grain-size and fabric were constructed by moving a circular sampling window of radius 4 mm across the scanned images at 4 mm intervals in both the vertical and lateral directions.

The following statistics were estimated for all sand grains inside the window: (a) the area-weighted mean grain size $\bar{D}_{\text{circle}}$, (b) the mean angle of grain long axes $\bar{\theta}_{\text{circle}}$, and (c) the mean resultant length $\bar{R}_{\text{circle}}$. The spatial distribution of $\bar{D}_{\text{circle}}$ was visualized as a heat map on the surface of the specimen. The pattern of the spatial distributions of grain fabric such as $\bar{\theta}_{\text{circle}}$ and $\bar{R}_{\text{circle}}$ were depicted as a vector-field map.

Characterization of Spaced Stratification Bands

Eight descriptive statistics were calculated from the grain data to quantitatively evaluate the characteristics of each band in spaced stratification. The boundaries of bands were identified by visual inspection of the polished sections.

The grain statistics for each band included: (1) the area-weighted mean grain size $\bar{D}_{\text{band}}$, (2) the standard deviation of grain size σ_{band} , (3) the mean angle of grain long axes $\bar{\theta}_{\text{band}}$, (4) the mean resultant length of grain long axes $\bar{R}_{\text{band}}$, (5) the standard deviation of vertical variation in mean grain

size σ_{vertical} , (6) the standard deviation of lateral variation in mean grain size σ_{lateral} , (7) the vertical trend of mean grain size I_{band} , and (8) the thickness of the band H_{band} .

Statistics σ_{vertical} and σ_{lateral} represent the spatial variability of grain-size distributions. Specifically, σ_{vertical} was calculated from the values of $\bar{D}_{\text{interval}}$ at every 4 mm vertical interval in each band, and σ_{lateral} was calculated similarly from the 4 mm lateral intervals. Statistics σ_{vertical} and σ_{lateral} are defined as:

$$\sigma_d = \sqrt{\frac{\sum_{i=1}^n (D_{d,i} - \bar{D}_d)^2}{n-1}}, \quad d \in \{\text{vertical, lateral}\} \quad (5)$$

where $D_{d,i}$ is the mean grain size in the i -th subinterval and $\bar{D}_d$ is the mean value across all intervals.

I_{band} was used to measure the degree of inverse grading in each band. It was defined as the regression coefficient between $\bar{D}_{\text{interval}}$ (calculated for every 4 mm interval) and the vertical coordinate in the band. Because grain size was expressed in the phi scale, a negative value of I_{band} indicates the presence of inverse grading. H_{band} was measured directly from the polished sections.

Multivariate Analysis of the Characteristics of Each Band

We conducted multivariate analyses of the descriptive statistics of sediment textures obtained from the bands of spaced stratification. Hierarchical-cluster analysis and linear-discriminant analysis (LDA) were applied to evaluate diversity of the microtextures, while principal-component analysis (PCA) was used to assess variability of grain-size and fabric in a two-dimensional PC space.

Hierarchical Cluster Analysis of Grain Imbrication Angles.---To examine the similarity of grain-size and fabric characteristics among bands, we focused on the distributions

of grain imbrication angles. Probability density distributions were obtained using a von Mises kernel density estimation (KDE) (Mardia and Jupp 2000). The bandwidth for KDE (h) was determined through the method of Taylor (2008).

The similarity between distributions was defined by the Jensen-Shannon divergence (JSD) (Lin 1991). The JSD between two probability distributions ($\mathbf{P}$ and $\mathbf{Q}$) is defined as:

$$\text{JSD}(P \parallel Q) = \frac{1}{2} \text{KLD}(P \parallel M) + \frac{1}{2} \text{KLD}(Q \parallel M), \quad (6)$$

where M is a mixture distribution of P and Q , and KLD denotes the Kullback-Leibler divergence:

$$\text{KLD}(P \parallel Q) = \sum_i P(i) \log \frac{P(i)}{Q(i)} \quad (7)$$

$$\text{KLD}(Q \parallel P) = \sum_i Q(i) \log \frac{Q(i)}{P(i)} \quad (8)$$

Smaller JSD values indicate greater similarity between two distributions.

The JSD values were used for hierarchical clustering in order to group bands with similar imbrication-angle distributions. The group-average method (Müllner 2011) was applied to calculate distances between clusters.

Linear-Discriminant Analysis of Band Statistics.---Linear-discriminant analysis (LDA) was performed to analyze the relationship between the clusters identified through the hierarchical-cluster analysis and other descriptive statistics of the bands. In this analysis, we used statistics 1, 2, and 5–8 (i.e., $\bar{D}_{\text{band}}$, σ_{band} , σ_{vertical} , σ_{lateral} , I_{band} , and H_{band}). The LDA allows us to evaluate which variables most effectively discriminate between band groups identified through clustering.

Principal-Component Analysis of Band Statistics.---Principal-component analysis (PCA) was conducted to summarize the overall relationship among bands on the basis of their descriptive statistics. This analysis included all eight sediment texture statistics 1–8, although mean values were excluded when statistical tests indicated multimodality. While hierarchical

clustering and LDA focus on group discrimination, PCA was used to visualize the dominant modes of microtexture characteristics across bands.

RESULTS

Sedimentary Facies

The Bandodani and Nada formations of the Izumi Group have been interpreted as submarine-fan deposits (Yamasaki 1986; Tanaka 1989). Three sedimentary facies are recognized in these formations (Fig. 6).

Facies I: Alternating Beds of Thin Sandstones and Mudstones.---Description:

Facies I consists of alternating beds of thin sandstone (0.1–0.6 m thick) and mudstone (0.1–0.4 m thick) (Fig. 7A). Mudstone beds are generally structureless, although some have faint lamination revealed by laminae of siltstone. Sandstone beds are composed of well-sorted medium- to very fine-grained sand, and are typically structureless or normally graded. Granule layers and parallel-laminated divisions occasionally are present at the bases and tops of sandstone beds. Spaced stratification is rarely observed in the thicker sandstone beds in this Facies (Fig. 7E). Beds are generally tabular in geometry, although sandstone beds locally show lenticular forms where they have scoured underlying mudstone and may pinch out laterally within a few meters.

Interpretation: Facies I is interpreted as a succession composed of deposits from high-concentration turbidity currents (Bouma 1962; Lowe 1982; Mutti 1992) interbedded with hemipelagites, most likely deposited in the submarine-fan lobes (Prélat et al. 2009). The fine-grained nature of this facies suggests deposition in the relatively distal parts of lobes or the interchannel areas between distributary channels on lobes (Zhang et al. 2015; Sychala et al. 2017). The normally graded or structureless divisions in the sandstone beds correspond to Bouma Ta or Lowe S3 divisions (Bouma 1962; Walker 1978; Lowe 1982), and parallel-laminated divisions correspond to Tb divisions, whereas Tc divisions are rare. Scour features

imply strong turbulence in the flows (Walker 1978; Mutti 1992), indicating that the structureless divisions are unlikely to represent en masse deposition from laminar debris flows or hyperconcentrated density flows (Mulder and Alexander 2001). Instead, rapid sedimentation from suspended load in turbulent flows could have produced these structureless divisions (Lowe 1982). Thus, despite its mud-prone character, this facies is interpreted to have formed in distal lobe or interchannel settings that were influenced by strongly turbulent sediment gravity flows.

Facies II: Sandstone-dominated Alternating Beds of Sandstone, Conglomerate, and Mudstone. ---Description: Facies II is composed of thick-bedded granule to sandstone beds interbedded with thin mudstone layers (Fig. 7B, C). The sandstones are mainly moderately sorted, medium- to very coarse-grained, and range from 0.1 to 0.6 m in thickness. Individual beds may amalgamate to form composite sandstone bodies several meters thick. These beds are laterally continuous with minor thickness variations and can be traced for hundreds of meters. This succession has no tendency toward upward thinning, and bed thickness varies considerably without a consistent trend in the vertical direction. Sandstone beds are normally graded and generally structureless, although parallel lamination is observed in the upper parts, and granule-rich inversely graded divisions (spaced stratification) are present locally in their basal parts (Fig. 7F). Cross-stratification is rare. Conglomerate beds of granule to pebble size also are present and typically have normal grading.

Soft-sediment-deformation structures are common, including flame structures, convolute lamination, and clastic dikes. Mud clasts, ranging from a few centimeters to 20 cm in diameter, are often incorporated into sandstones and conglomerates and are often concentrated in the upper intervals of structureless sandstones, where they grade into parallel-laminated intervals. Bioturbation is generally weak, although *Ophiomorpha rudis* and large burrows of *Archaeozostera* are observed in some sandstone beds. Flute and groove casts are present at sandstone

bases. Mudstone beds, 0.1–0.4 m thick, are composed mainly of clay, but some beds are composed of silt and show weak bioturbation.

Interpretation: Facies II is interpreted as the product of high-concentration turbidity currents deposited in the proximal regions of submarine-fan lobes. The thick-bedded sandstones and conglomerates with normal grading reflect waning turbulent flows, comparable to those in the Lowe sequence (Lowe 1982). Importantly, the presence of normal grading demonstrates progressive deposition from turbulent flows and excludes interpretation as en masse deposition from laminar debris flows. The overlying parallel-laminated sandstones and mudstones correspond to Bouma Tb–Te divisions (Bouma 1962), reflecting the transition to lower-concentration flow conditions. The presence of large mud clasts suggests erosion of unconsolidated muddy substrates by energetic, high-shear flows (Li et al. 2017). The trace-fossil assemblage, including *Ophiomorpha rudis* and *Archaeozostera*, is consistent with deposition in a deep-marine environment in the *Zoophycos–Nereites* Ichnofacies (Uchman 2009; Kikuchi and Kotake 2013). Although the sandstone-dominated nature of this facies suggests channel fills, several features argue against this interpretation. First, sandstone beds in this facies are laterally continuous and levee deposits are absent, excluding the possibility of confined-channel systems. Second, the facies does not show systematic upward-thinning trends characteristic of lobe fringes or channel–levee successions. Instead, bed thickness varies irregularly, suggesting compensational stacking, in which successive turbidity-current lobes filled topographic lows on the fan surface (Mutti 1992; Prélat et al. 2009; Straub et al. 2009). Taken together, these characteristics support the interpretation of Facies II as deposits of lobes, in which frequent avulsion and stacking of lobe elements produced laterally extensive, sand-rich successions without well-developed levee complexes (Posamentier and Kolla 2003; van der Merwe et al. 2014; Maier et al. 2020).

Facies III: Very Thick Conglomerates with Sandstone Beds.---Description: Facies III consists of very thick conglomerate beds overlain by coarse-grained sandstone beds. The

conglomerates are more than 2.0 m thick. In contrast, the sandstone beds range from 0.3 to 0.8 m in thickness (Fig. 7D). Bed thickness varies considerably, and localized scour structures up to approximately 20 cm deep are often observed at their bases (Fig. 2). The conglomerates are composed of poorly sorted, clast-supported, sub-rounded to sub-angular pebbles. They are either normally graded or structureless. Coarse to very coarse sandstone beds, commonly showing parallel lamination, overlie these conglomerates in several places. Mudstones are absent from this facies, and mud clasts are rare in both the conglomerates and sandstone beds. No evidence of bioturbation has been observed.

Interpretation: This facies is interpreted as deposits of high-concentration gravity flows in the regions of submarine lobes near the channel. The clast-supported conglomerates and overlying sandstone beds are attributed to deposition from high-concentration turbidity currents or debris flows. Normally graded conglomerates and sandstones, corresponding to the R3 and S3 divisions of the Lowe sequence (Lowe 1982; Postma et al. 1983; Chun and Chough 1992), are thought to have formed mainly from suspension settling in high-concentration flows (Lowe 1982). The parallel lamination in the overlying sandstone beds suggests deposition by low-concentration turbidity currents that developed from rarefied high-concentration flows after gravel deposition (Lowe 1982; Mulder and Alexander 2001).

Facies III is further interpreted as representing deposition in the channel-lobe transition zone (CLTZ), where rapid flow deceleration happens because of channel widening and reduced slope (Kenyon et al. 1995; Wynn et al. 2002). Such conditions promote the formation of hydraulic jumps in turbidity currents. Eddies generated by hydraulic jumps cause basal erosion and entrainment of muddy sediments (Brooks et al. 2022). Rapid deposition from decelerating flows in this zone produces poorly sorted, coarse-grained, structureless sandstone beds. The features of Facies III are consistent with this interpretation. The overall thickness and coarse-grained nature indicate deposition in more proximal areas than other facies. The absence of mudstone intercalations and

the scarcity of mud clasts suggest frequent flows that repeatedly winnowed unconsolidated hemipelagic mud from the depositional environment.

Lobe-Complex Facies Association. ---Description: This facies association consists of repeated successions of Facies I, II, and III. Mud-prone successions (Facies I) and sandstone-dominated successions (Facies II) alternate repeatedly, with conglomerate beds (Facies III) abruptly intercalated in the sandstone-dominated successions of Facies II. Bed thickness varies irregularly, and no overall upward-thinning or upward-thickening trend is observed. Facies I and Facies II are characterized by tabular, moderately continuous beds extending over several meters to tens of meters. In contrast, Facies III beds have poor lateral continuity and highly variable thickness.

Interpretation: This facies association, composed of Facies I, II, and III, is interpreted as deposits of a submarine lobe complex. Such lobe complexes represent tongue-shaped architectural elements that develop at the distal ends of leveed channels or submarine canyons (Mutti and Normark 1987; Galloway 1998; Posamentier and Walker 2006). Facies I is interpreted as representing distal lobe deposits, whereas Facies II and Facies III correspond to proximal lobe deposits and the channel-lobe transition zone, respectively. The observed alternation between Facies I and Facies II successions is attributed to local variations in lateral channel shifting or avulsion (Posamentier and Kolla 2003; Grundvåg et al. 2014), to compensational stacking (Straub et al. 2009), or to migration of lobe depocenters in response to sea-level fluctuations (Hodgson et al. 2006; Grundvåg et al. 2014).

An alternative interpretation is that these deposits represent channel fills in submarine fans. However, several diagnostic features of channel-fill deposits are absent in this facies association. Channel fills are typically characterized by systematic upward-fining successions, erosionally based channel-form geometries, and thick mud-prone levee deposits (Posamentier and Kolla 2003; van der Merwe et al. 2014). In contrast, the present facies association shows vertical variation in bed thickness without systematic trends, tabular rather than channel-shaped

geometries, and an absence of thick levee successions. Although small-scale distributary channels (less than 10 m deep) may develop on lobe surfaces (Posamentier and Kolla 2003), these can be distinguished from fully developed leveed-channel systems by their limited depth and lack of associated levee deposits, which are also absent here.

Visual Observation of Spaced Stratification

Spaced stratification was observed in the lowermost parts of the sandstone beds of Facies I and II, overlain by either a parallel-laminated or structureless division. In this study, spaced stratification generally consisted of 2–5 bands. Each band had an internal erosional surface at its base (Fig. 3). Inverse grading was commonly observed immediately above the basal surfaces of the bands. Most bands showed grain-size variation only near the base and were structureless in their upper parts, although several thin bands (2–3 cm thick) had inverse grading throughout (Fig. 3A).

The thickness of the spaced stratification intervals ranged from approximately 10 to 20 cm, and individual bands ranged from 12 to 64 mm. Spaced stratification was laterally continuous over several meters, but the internal erosional surfaces often became indistinct. All bands were composed of sand grains with diameters of approximately 0.5–2.0 ϕ (0.71–0.25 mm), most of which were subrounded. Further subdivision of bands in the spaced stratification, on the basis of grain size or visible sedimentary structures, was not possible through visual inspection.

Microtextural Characteristics of Spaced-Stratification Bands

Training and Test Results of the CNN Model.---The trained CNN model for image analysis demonstrated high performance in extracting sand grains from sandstone cross-sectional images. The Dice coefficient for the validation dataset reached 0.787 when trained with Tanimoto loss and Momentum SGD. In addition, the RMSE values for mean grain size and mean grain orientation were 0.215 and 0.187, respectively (Fig. 8), indicating close agreement with manually traced ground-truth data in the mean values.

RMSE evaluates agreement in the average values of the data and cannot directly reflect differences in the grain fabric, i.e., imbrication angle distributions. The performance of the trained CNN model on the grain fabric was additionally assessed, as described in the following section on grain fabric.

Grain Size.---The grain-size distributions of all bands of spaced stratification were unimodal, with peaks ranging from 1.5 to 2.5 ϕ (0.35–0.18 mm). The null hypothesis of unimodality of the distributions in all measured samples was not rejected by the Dip Test (Fig. 9A; Table 1). The area-weighted mean grain size ranged from 0.0 to 1.7 ϕ (1.0–0.31 mm), while the standard deviation (sorting) ranged from 0.7 to 1.1 ϕ (0.62–0.47 mm) (Figs. 10A, B, 11A, B, and figures shown in the Supplemental Material). The mean grain sizes generally differed from the modal values, reflecting positively skewed distributions (0.01–0.39). Mean grain size and standard deviation were positively correlated; in other words, coarser bands tended to be more poorly sorted. For example, coarse-grained bands (average grain size < 0.5 ϕ) observed in the Bandodani Formation (Figs. 10A, B) exhibited broader distributions, with sorting values exceeding 0.9 ϕ .

Vertical trends in grain size in the bands varied depending on band thickness. As observed visually, thinner bands (2–3 cm thick) had inverse-grading throughout, from base to top (e.g., Fig. 10A). In contrast, thicker bands (> 4 cm) displayed inverse-grading only in the basal interval (approximately 1 cm), while their upper parts were structureless or normally graded (Fig. 11A).

The average area composition in each band consisted of approximately 37% grains and 63% matrix. These values were calculated from the number of black and white pixels contained within each band image. However, as described in the Methods section, particles finer than silt size are difficult to distinguish. Therefore, the matrix includes silt, clay, and potentially misclassified sand grains. The grain–matrix area composition was not used in later analyses because of technical limitations.

Grain Fabric.---The grain-fabric characteristics of bands in spaced stratification were classified into two types; Types A and B. A hierarchical-cluster analysis on the basis of the similarity between imbrication-angle distributions clearly distinguished these two types (Fig. 12). The distance between the two clusters was larger (0.13) than the within-cluster distributions, which ranged from approximately 0.01 to 0.08. The features of these fabric types are described below. All the following features are results of sections cut parallel to the flow direction. Sections perpendicular to the direction of the flute casts, and the peak of the long-axis orientation of sand grains included in the horizontal plane (Fig. 9B) were also analyzed. However, fewer sections had significant imbrication angles compared to sections parallel to the flow. Therefore, we analyzed sections parallel to the flow.

Type A fabric has bimodal distributions (Fig. 9B). The null hypothesis of unimodality was occasionally rejected for Type A datasets (Table 1). The observed angle distributions were well approximated by a mixture of two von Mises distributions (Fig. 10C, and figures shown in the Supplemental Material). The dominant peaks in the distributions corresponded to high imbrication angles ($> 40^\circ$), whereas the subordinate peaks corresponded to downstream-dipping imbrications ($< -40^\circ$). The mean resultant lengths (vector concentrations) of Type A distributions were low (typically < 0.3) (Fig. 10D).

In contrast, Type B fabric is characterized by a unimodal distribution of grain-imbrication angles (e.g., Fig. 9B). The mean imbrication angles were generally lower than the dominant peaks of Type A, ranging from 15 to 30° . Grain orientations were strongly concentrated around the mean, resulting in higher mean resultant lengths than those of Type A, which often exceed 0.3.

To confirm that the observed differences between the two fabric types were not artifacts of image analysis on the basis of biased training data, manually traced images were compared with

the results of automated analysis. The comparison demonstrated that both bimodal and unimodal-angle distributions were present in the manually obtained data as well (Fig. 13).

High-resolution analyses further indicated that the two fabric types did not result from vertical heterogeneity in a single band. In Type A bands, grain fabric measured at 4-mm intervals consistently showed bimodal distributions of imbrication angles from base to top. By contrast, Type B bands had unimodal imbrication-angle distributions throughout their thickness. Several Type A bands had an upward increase in imbrication angle (Fig. 10C), whereas most of the Type B bands had little change across their thickness (Fig. 11C). Finer-grained intervals tended to have more unimodal long-axis orientations.

Multivariate Analysis of Descriptive Statistics of Bands for Two Fabric Types

To investigate whether Types A and B vary continuously and to examine how each type relates to other textural characteristics, we conducted linear-discriminant analysis (LDA) and principal-component analysis (PCA) on the descriptive statistics of grain size and band thickness. The results indicated that variations in grain-size distribution and band geometry are associated systematically with differences in grain-fabric type.

The LDA results revealed that several descriptive statistics effectively distinguish the two fabric end-member clusters (Fig. 14; Table 1). The linear discriminant function indicated that Type A bands are characterized by a coarser mean grain size (coefficient = -2.48) and better sorting (coefficient = -0.93). Statistics describing vertical and lateral variations in grain size (σ_{vertical} , σ_{lateral} , and I_{band}) were also significant; the coefficient for σ_{vertical} (-0.37) and I_{band} (-0.67) suggests that Type A bands have stronger inverse grading than Type B. In addition, lateral variation in grain size (σ_{lateral} , -0.17) and band thickness (H_{band} , -0.76) contributed to the discrimination between the two fabric clusters. Overall, the discriminant function correctly classified the bands into the two fabric types with 100% accuracy. We additionally performed

leave-one-out cross-validation (LOOCV) to assess the robustness of this classification and to test for overfitting, yielding a classification accuracy of 85.7%. Although the 100% accuracy was affected by the small sample size, the LOOCV results supported this classification.

The PCA conducted without including imbrication-angle data produced consistent results. The first two principal components explained approximately 42% and 18% of the total variance, respectively (Table 2). PC1 and PC2 explained approximately 60% of the total variance, indicating that the PC1–PC2 plot captures the major trend in the dataset but does not represent all textural variability. In the PC1–PC2 space (Fig. 15), Type A bands tend to have lower scores of PC2, whereas Type B bands have higher PC2 scores. A lower PC2 score represents coarser mean grain size, less grain-size variation, weaker vertical variation, greater lateral variation, stronger inverse grading, and lesser thickness. On the other hand, a higher PC2 score reflects finer mean grain size, greater overall grain-size variation, greater vertical variation, greater lateral variation, stronger inverse grading, and lesser thickness (Table 2). The eigenvectors of PC1 and PC2 indicate that these tendencies are broadly consistent with the LDA results.

DISCUSSION

Advantages of CNN-based Semantic Segmentation for Grain Microtextural Analysis

The methodology developed in this study has two key novelties: the use of a convolutional neural network (CNN) for semantic segmentation and its application to the analysis of sedimentary rocks. While CNN-based image analysis has become a widely adopted tool in geology and related disciplines (e.g., Zhao et al. 2017; Ronneberger et al. 2015), this study demonstrates its utility in sedimentary-rock microtexture analysis by use of a ResUNet architecture, a model known for its reliability and accuracy in semantic segmentation tasks (Diakogiannis et al. 2020; Shang et al. 2021). The segmentation accuracy for sandstone cross-sections from the study area reached ~

80% when compared with manual tracing (Fig. 8), confirming that the model is sufficiently robust to identify grain boundaries even in scanned, polished sections that are less distinct than thin sections (Fig. 13).

Previous studies of spaced stratification relied on thin-section observations to measure grain size and imbrication (e.g., Hiscott and Middleton 1980; Yagishita 1994). Although effective for targeted observations, thin-section preparation is time-consuming—often requiring hours for both preparation and grain tracing—and inherently limited in scale. For instance, Hiscott and Middleton (1980) analyzed ~ 100 grains per sample, whereas Yagishita (1994) measured ~ 200 grains, thereby limiting the statistical robustness of both analyses. By contrast, the present method extracted 1,000–20,000 grains from ~ 10 cm² cross-sectional images of spaced-stratification bands. This combination of large-scale coverage and fine-scale resolution enables multivariate analyses, systematic comparisons (Figs. 12, 14, 15), and visualization of characteristics (Figs. 10, 11, 16) across multiple stratification bands.

The combination of wide-area polished-section imaging and CNN-based segmentation offers a powerful framework for sedimentary rock analysis. Beyond spaced stratification, it can be extended to sandstones with diverse diagenetic conditions, enabling quantitative and statistical analyses of microtextures across a broad spectrum of sedimentary features. This approach thus broadens the methodological foundation for the study of sedimentary textures and structures at multiple scales.

Origin of the Two Fabric Types of Spaced-Stratification Bands

Two distinctive grain-fabric types, Type A and Type B, were identified in sandstones with spaced stratification (Figs. 10, 11). Type A has a clearly bimodal distribution of imbrication angles, with peaks at approximately –40° and 40–50°, whereas Type B shows a unimodal, upstream-dipping orientation centered around 20° (Fig. 9B). Both fabric types occur in the high-concentration turbidites of Facies I (distal lobe) and Facies II (proximal lobe), and no relation to

sedimentary facies was found (Fig. 2). In contrast, spaced stratification was not found in deposits from the channel-lobe transition zone (CLTZ; Facies III).

This spatial pattern suggests that the development of spaced stratification is not controlled solely by facies type, but rather by local hydraulic conditions that fluctuate during sedimentation. Environments such as the CLTZ, where flow velocity and turbulence intensity vary frequently because of the shifting position of the hydraulic jump (Ono et al. 2023), appear to be unfavorable for its formation. The coexistence of both Type A and Type B fabrics in Facies I and II further implies that spaced stratification can develop under a range of depositional settings once certain hydrodynamic thresholds are met, reflecting the complex and possibly non-unique relationship between formative flow processes and resultant sedimentary structures.

The bimodal grain fabric observed in Type A has rarely been reported previously in deep-sea sandstones. Although Baas et al. (2007) described bimodality in bedding-parallel grain orientations in deep-sea sandstones, and several structureless deposits described by Hiscott and Middleton (1979) and Hein (1979) have bimodal distributions of imbrication angles. However, no prior studies have documented such a distinct bimodal pattern in imbrication angles in spaced stratification bands.

A possible reason Type A fabrics have been overlooked in earlier studies is the limited number of measured grains (typically fewer than 200 per sample). When grain fabrics have a unimodal distribution, a reliable mean orientation of grain long axes can be estimated from as few as ~ 200 measurements (e.g., Baas et al. 2007). In contrast, for bimodal grain fabrics, the weaker mode may consist of only several tens of grains. This results in substantial estimation errors and makes it statistically difficult to distinguish the minor mode from the dominant peak. Consequently, conventional analytical approaches are likely inadequate for reliably detecting multimodal grain fabrics.

The formation mechanism of Type A remains uncertain, but multivariate analyses provide clues to possible controls. Linear-discriminant analysis (LDA) clearly distinguishes between Type A and Type B (Fig. 14), with Type A occurring preferentially in coarser sandstones. Principal-component analysis (PCA) further demonstrates that grain size correlates with fabric type (Fig. 15), suggesting that higher shear-stress conditions may promote the development of bimodal fabrics. This interpretation aligns with the idea that traction-carpet processes involve intense grain–grain interactions (Rees 1968), which can generate high-angle imbrication ($\sim 30\text{--}40^\circ$), one of the peaks observed in Type A. However, the occurrence of a second orientation peak (Fig. 9B) is not predicted by existing traction-carpet models, indicating that Type A cannot be simply interpreted as their product.

Alternative genetic interpretations also merit consideration, such as antidune migration and the formation of low-amplitude bedforms, which have been proposed as potential mechanisms for spaced stratification (Best 1992; Miyata and Tanaka 2011). Grain-fabric data from laboratory antidunes (Yagishita and Taira 1989) are generally unimodal, showing $\sim 20^\circ$ upstream dips—similar to Type B—but some downstream-slope samples suggest a weak bimodality. Because those experiments included only ~ 200 measured grains, the statistical evidence remains inconclusive. Considering our results (Fig. 9B), antidune migration remains a plausible mechanism for the development of Type A, although further experimental replication with larger sample sizes is required to substantiate this interpretation. Moreover, recent flume studies of supercritical-flow bedforms (MacDonald et al. 2009) reported oscillations in flow direction during bedform development, which could likewise account for the bimodal imbrication characteristic and lateral variation of fabric (Fig. 16) of Type A.

Another possible explanation is that bimodal fabrics result from strong flow instabilities or flow reversals. Kneller et al. (1991) demonstrated that turbidity currents reflecting off obstacles may undergo repeated reversals, and subsequent experiments confirmed that Kelvin-Helmholtz

instabilities can induce velocity fluctuations in density flows (Kneller et al. 1997; Sakai et al. 2002). Such oscillatory flow could generate alternating flow directions and produce bimodal grain imbrications. Our observations of Type A may therefore record episodes of unstable or reversing flow in high-density currents, leaving a sedimentary signature of bimodality.

By contrast, Type B is characterized by unimodal, upstream-dipping imbrication at $\sim 20^\circ$ (Fig. 9B), closely resembling fabrics associated with parallel lamination (Arnott and Hand 1989). Nevertheless, the presence of Type B in spaced-stratification beds lacking fine-scale lamination (Fig. 11) indicates that these deposits cannot simply be equated with planar lamination.

The coexistence of two distinct fabric types implies that spaced stratification is not genetically uniform but instead represents a composite category that may encompass deposits formed by various processes. Type A tends to occur in slightly coarser and thinner bands (Fig. 10), whereas Type B is more common in finer ones. Because these differences are subtle and often imperceptible in the field, they may have been overlooked, contributing to the long-standing assumption that spaced stratification represents a single genetic type.

The recognition of two fabric types, supported by multivariate analyses (Figs. 12, 14, 15), suggests that spaced stratification in this study area encompasses at least two distinct depositional processes. These findings highlight the need for targeted flume experiments and numerical modeling to reproduce such fabrics under controlled flow conditions and to evaluate whether traction carpets, antidune migration, or flow reversals are responsible.

It should also be noted that further analyses incorporating a large number of samples from various depositional settings are required to evaluate the generality of these findings, because this study is based on a limited number of beds from two formations in a single basin. By establishing diagnostic criteria for fabric variability, this study provides a basis for more

refined interpretations of high-energy sediment transport and the paleoenvironmental significance of spaced stratification.

CONCLUSIONS

This study demonstrates that quantitative analysis of wide-range and grain-scale microtextures provides new constraints on the formation processes for spaced stratification. This study develops a deep-learning-based image-analysis method using a CNN-semantic-segmentation model to identify and measure sand grains in cross-sectional images of sedimentary rocks with micrometer-scale resolution and approximately 80% accuracy. The method allows rapid and reproducible quantification of grain size and orientation, completing analyses in several minutes per 10 cm² sample. This approach enables objective characterization of sedimentary microtextures that were previously difficult to quantify, providing a new framework for the study of sedimentary fabrics and textures.

Analysis of coarse-grained sandstones with spaced stratification from the Upper Cretaceous Izumi Group suggested previously unrecognized microtextural variability in the inversely graded bands. Using the CNN-based image analysis, we found that spaced stratification is not uniform but comprises two distinct microstructural types: (1) **Type A**, characterized by bimodal distributions of grain-imbrication angles, coarser mean grain size, and larger within-band variation in both grain size and fabric; and (2) **Type B**, characterized by unimodal, upstream-dipping imbrication, finer mean grain size, and smaller internal variation. These two types exist even within the same depositional settings, indicating that they are not facies-dependent but instead reflect different depositional dynamics. These findings suggest that spaced stratification may be a composite product of more than one depositional process.

Further experimental and numerical studies are needed to reproduce these microtextures under controlled-flow conditions. Comparing the results of such simulations with the microtextural characteristics identified here will help determine whether traction carpets, antidune migration, or

unsteady flow structures are responsible for the formation of spaced stratification. The present study thus provides both a methodological advance and a new empirical foundation for understanding the microphysical processes that govern high-energy sediment transport in deep-marine environments.

DATA AVAILABILITY STATEMENT

Detailed descriptions of the CNN workflow of this study are provided in the Supplementary Materials. The images of the samples, the analyzed results, the CNN training and testing datasets, and the code used for the CNN and analysis are available in the open-access repository Zenodo at <https://doi.org/10.5281/zenodo.17295663>.

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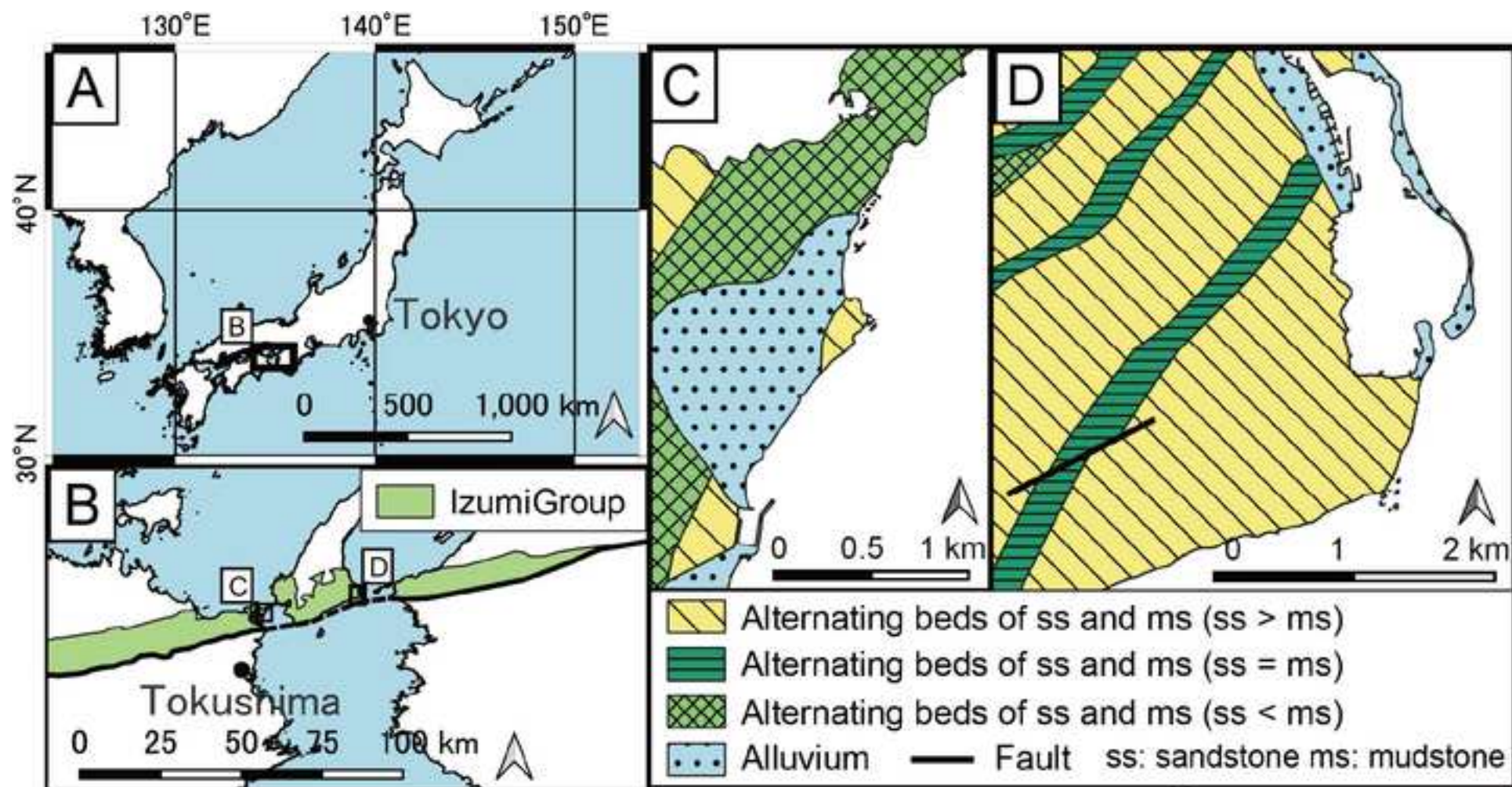
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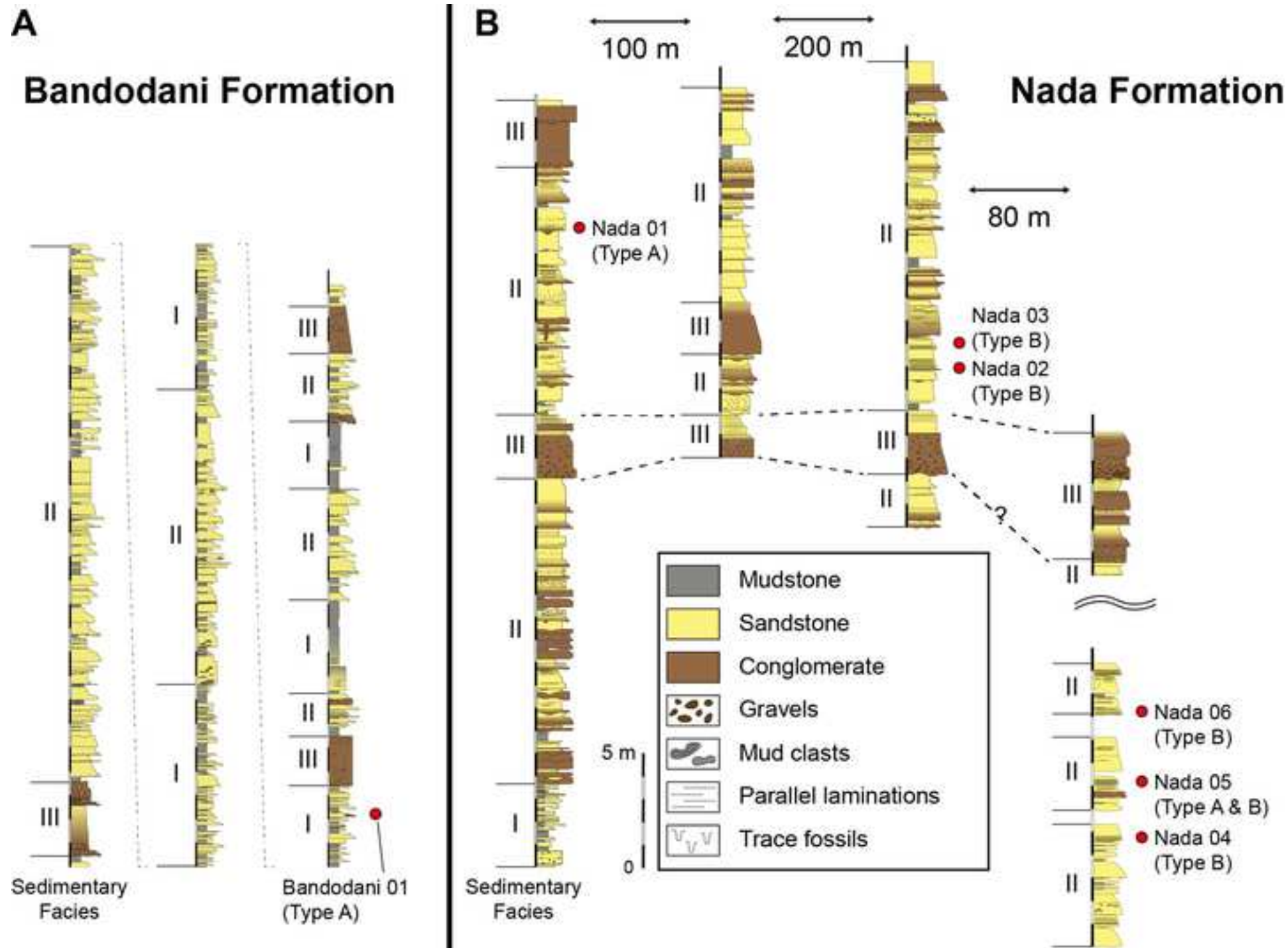
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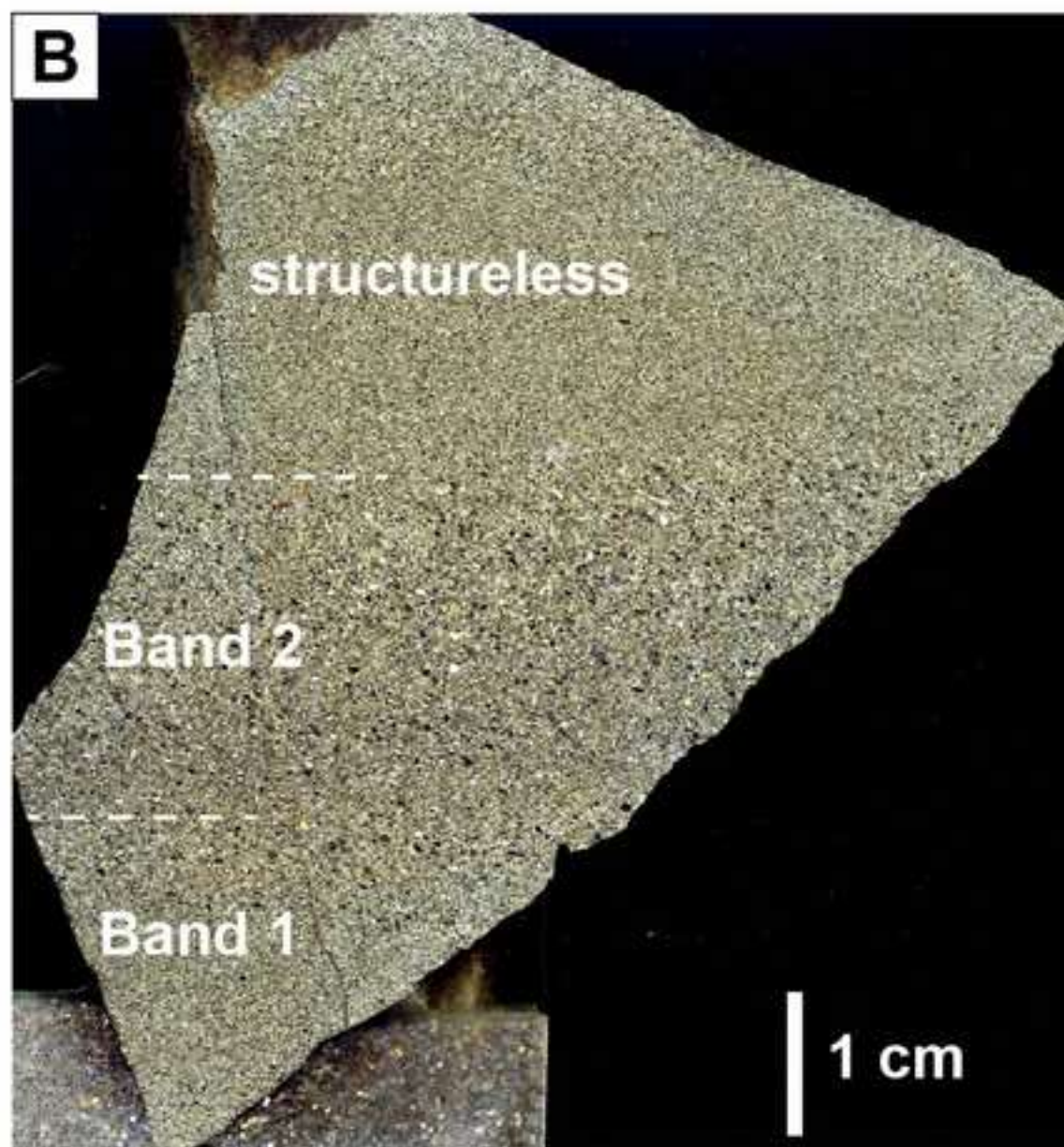
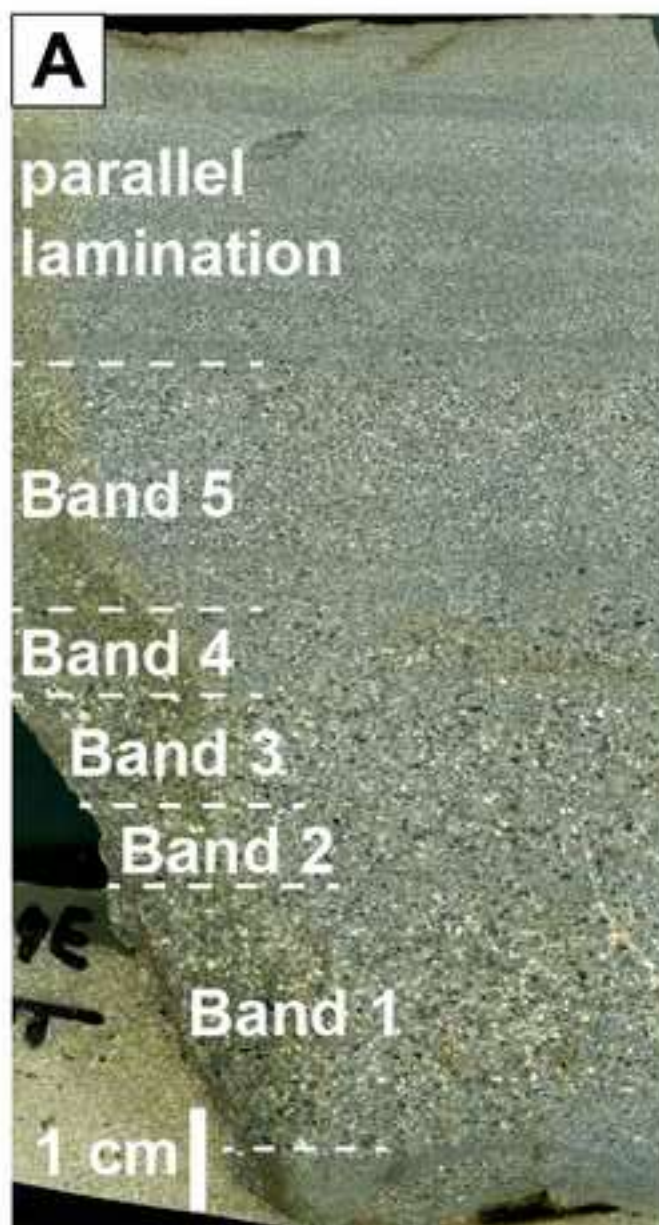
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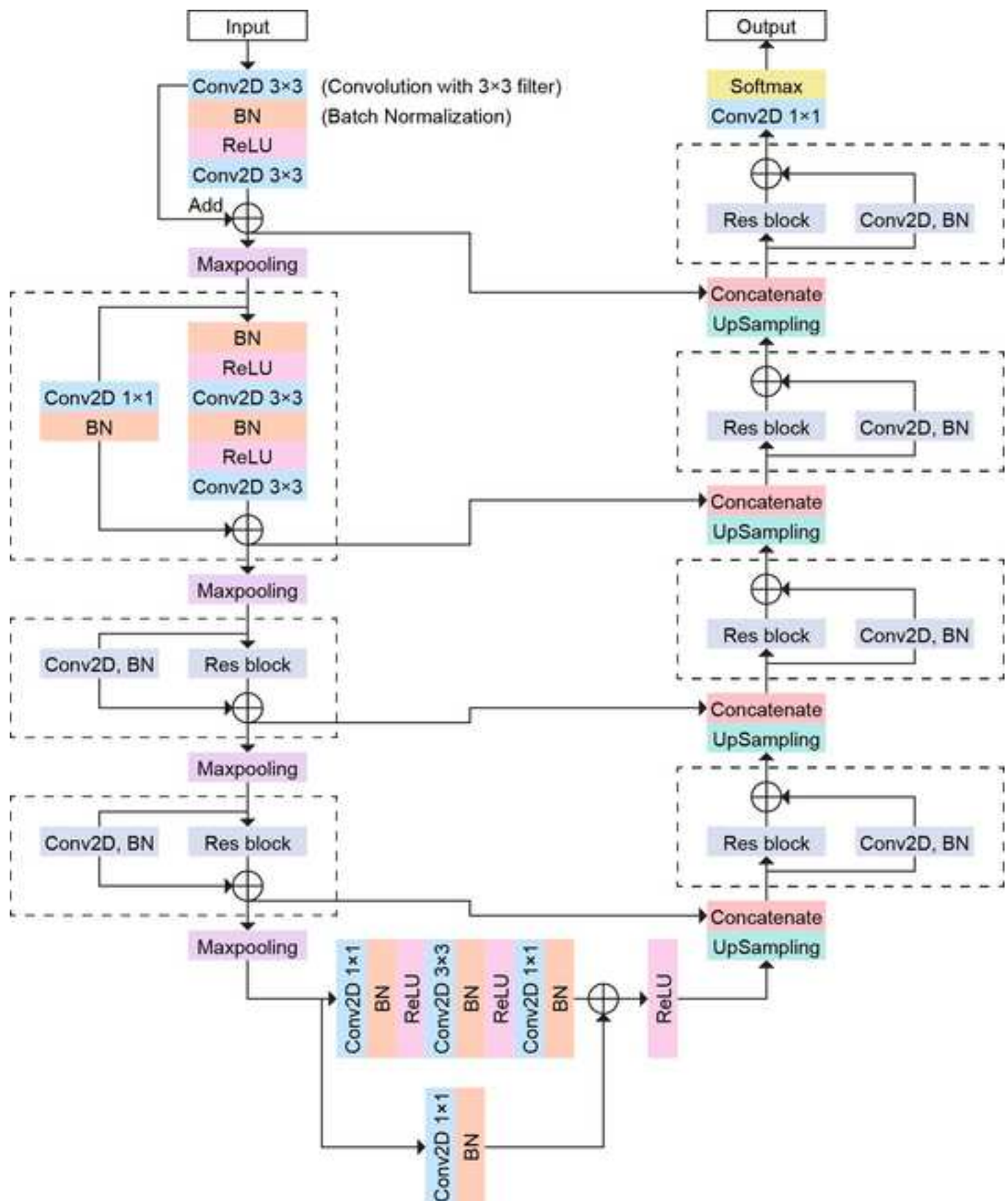
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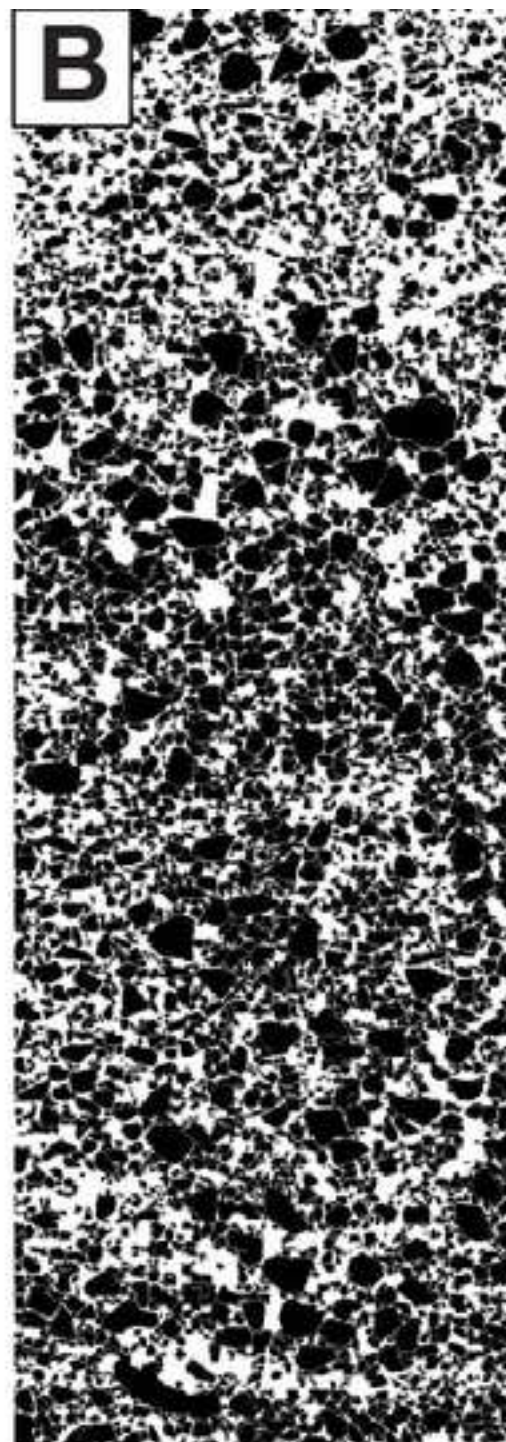
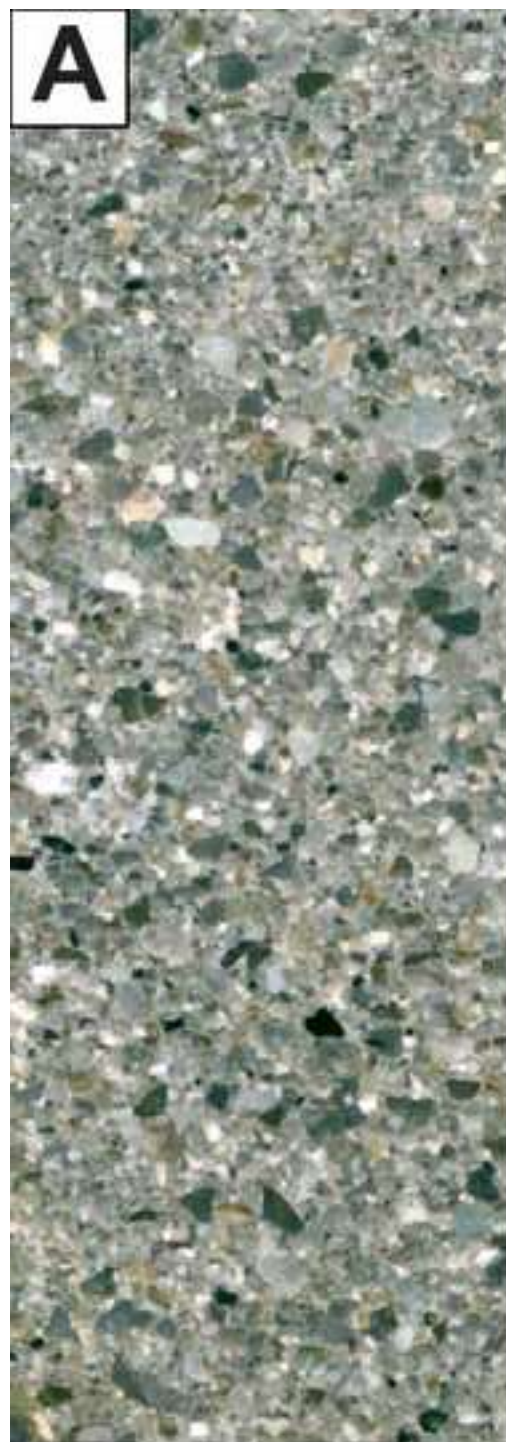




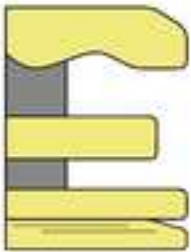
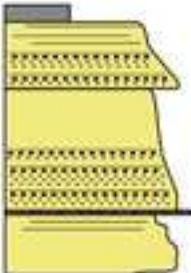


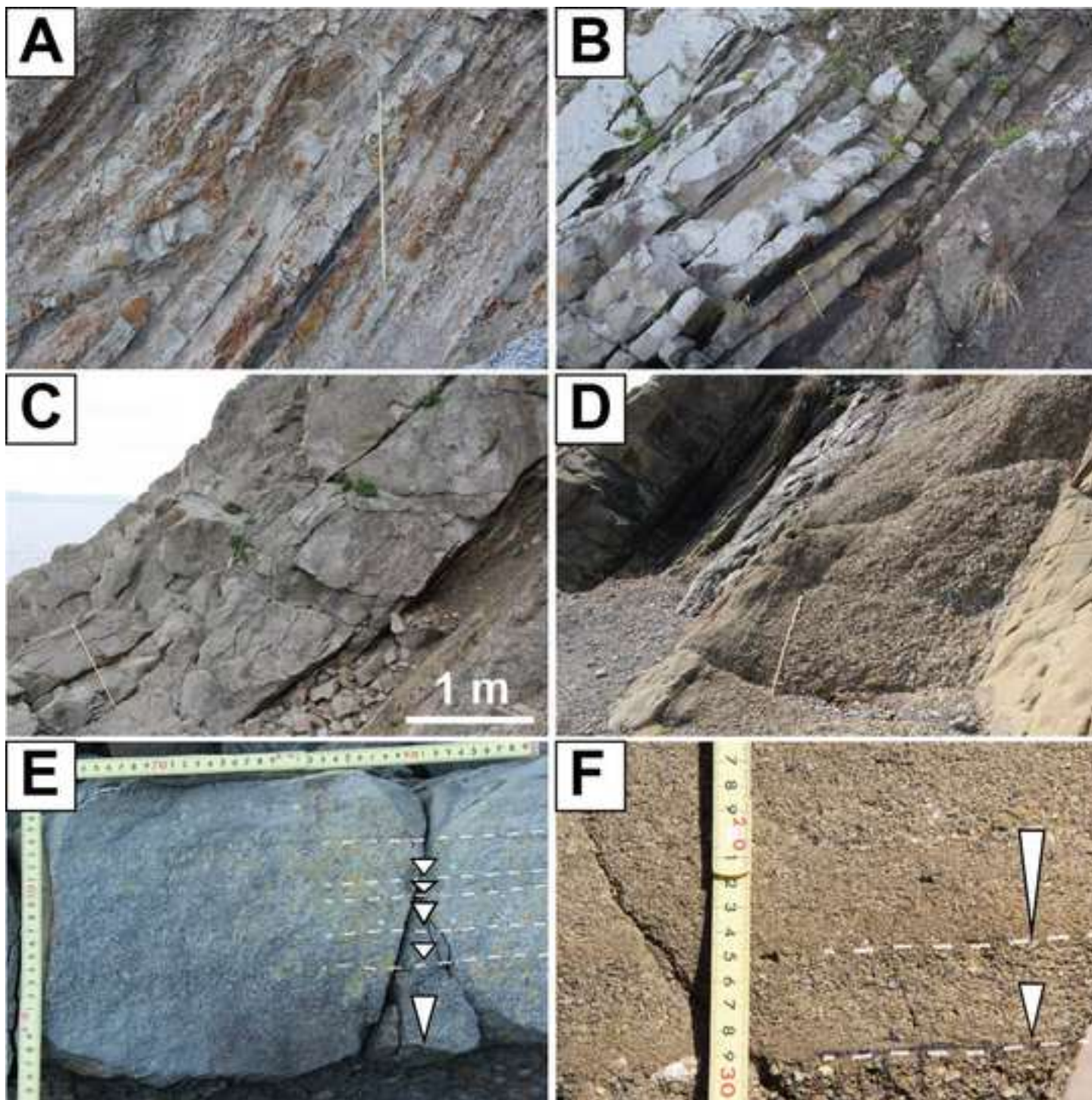
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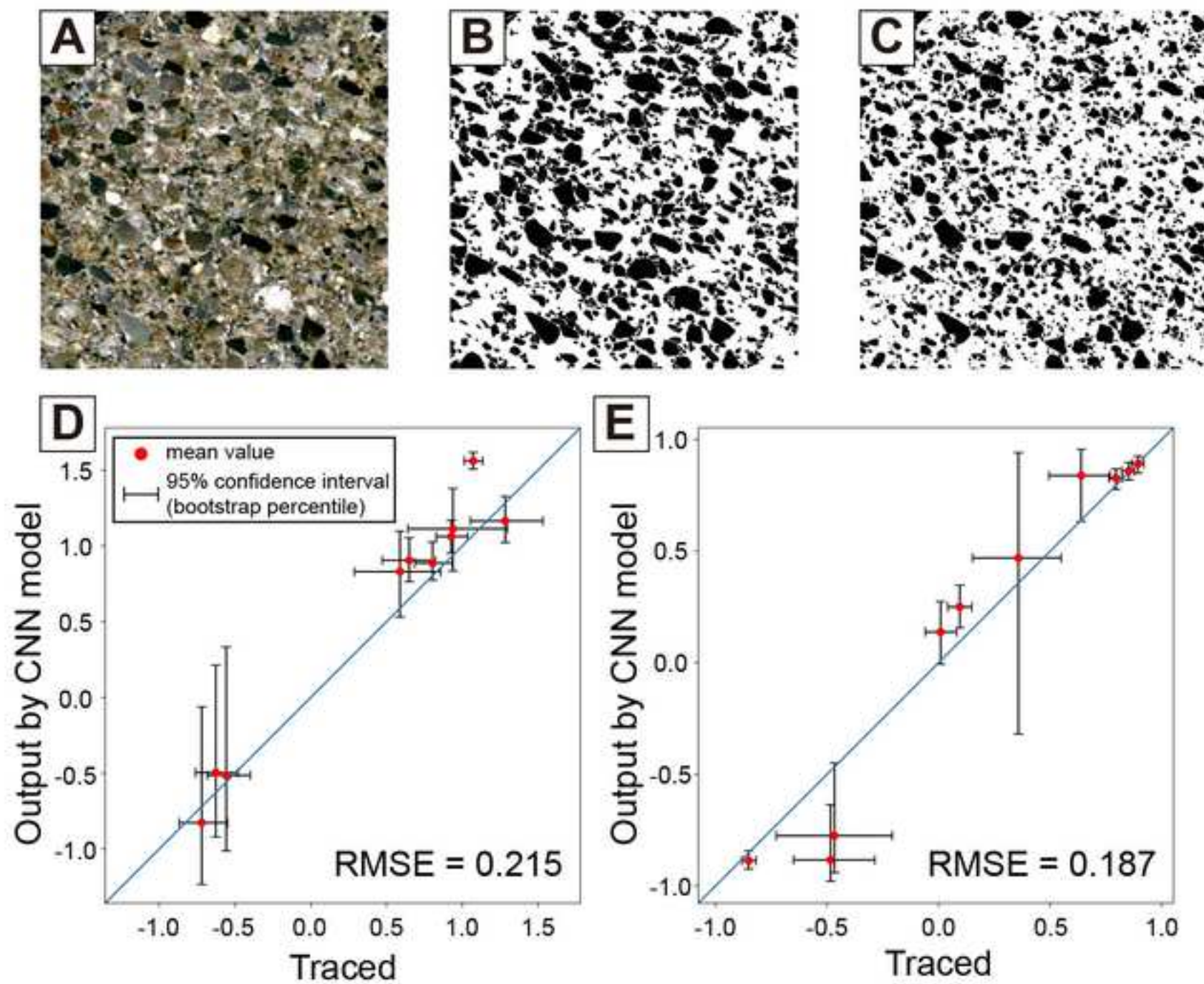


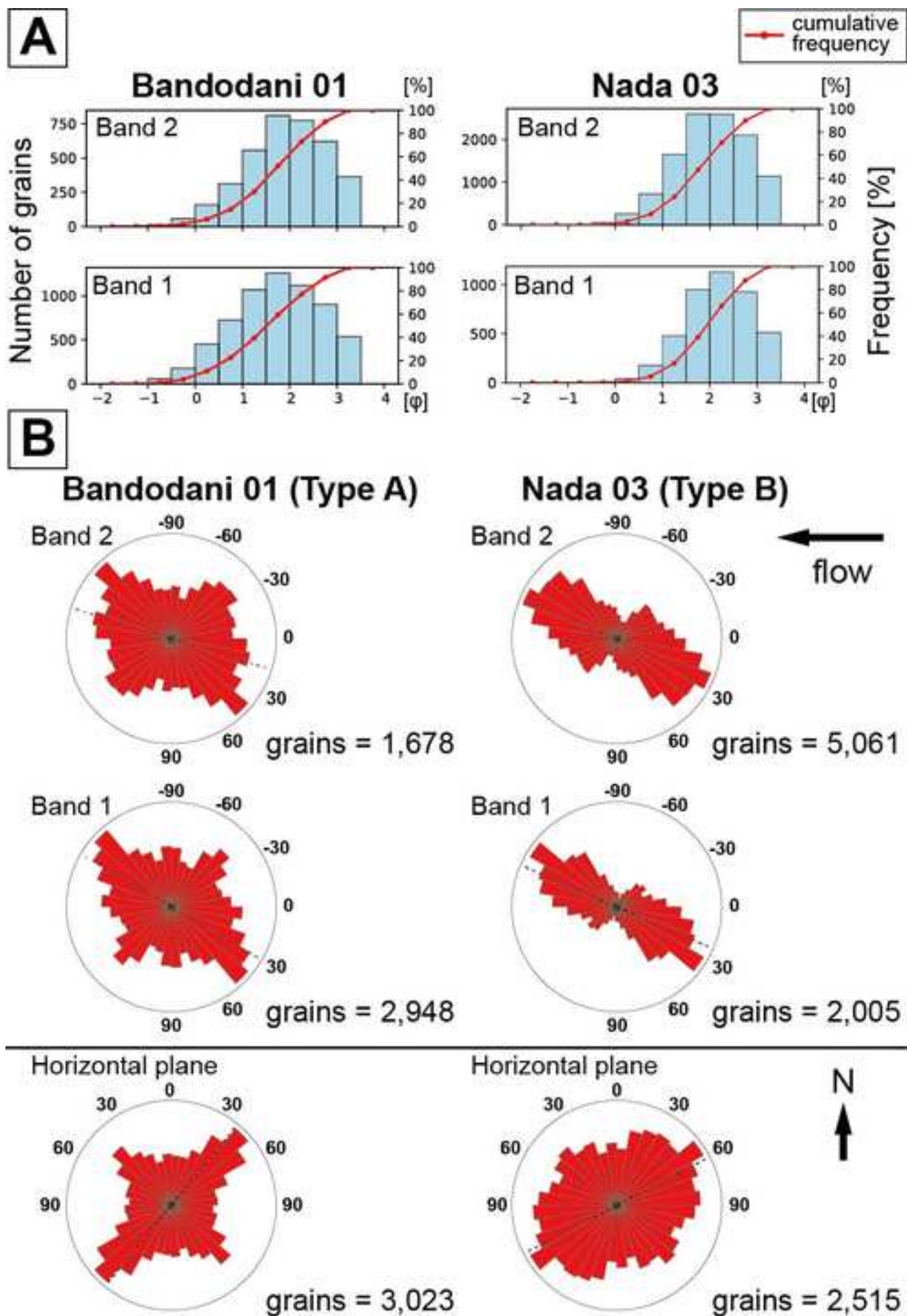


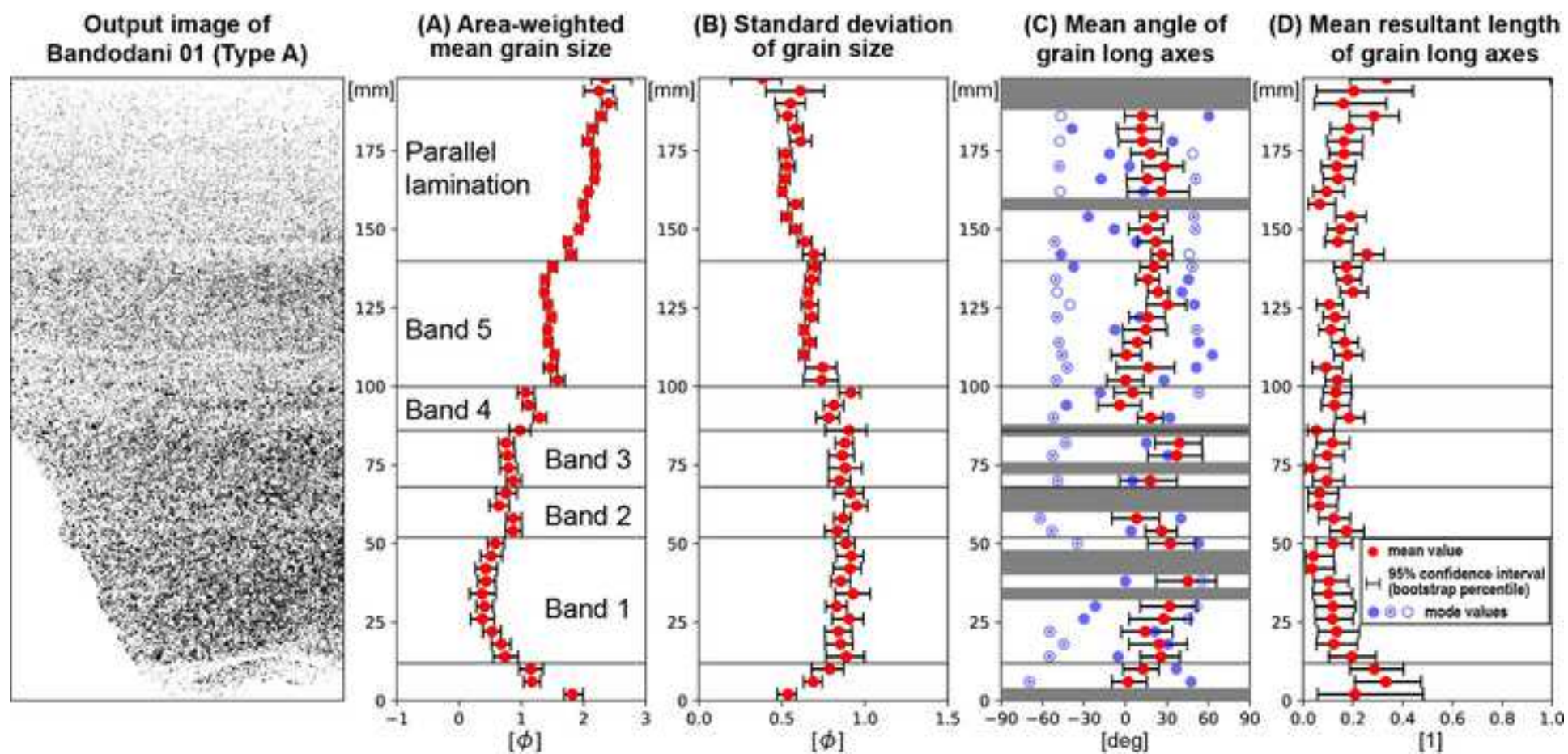
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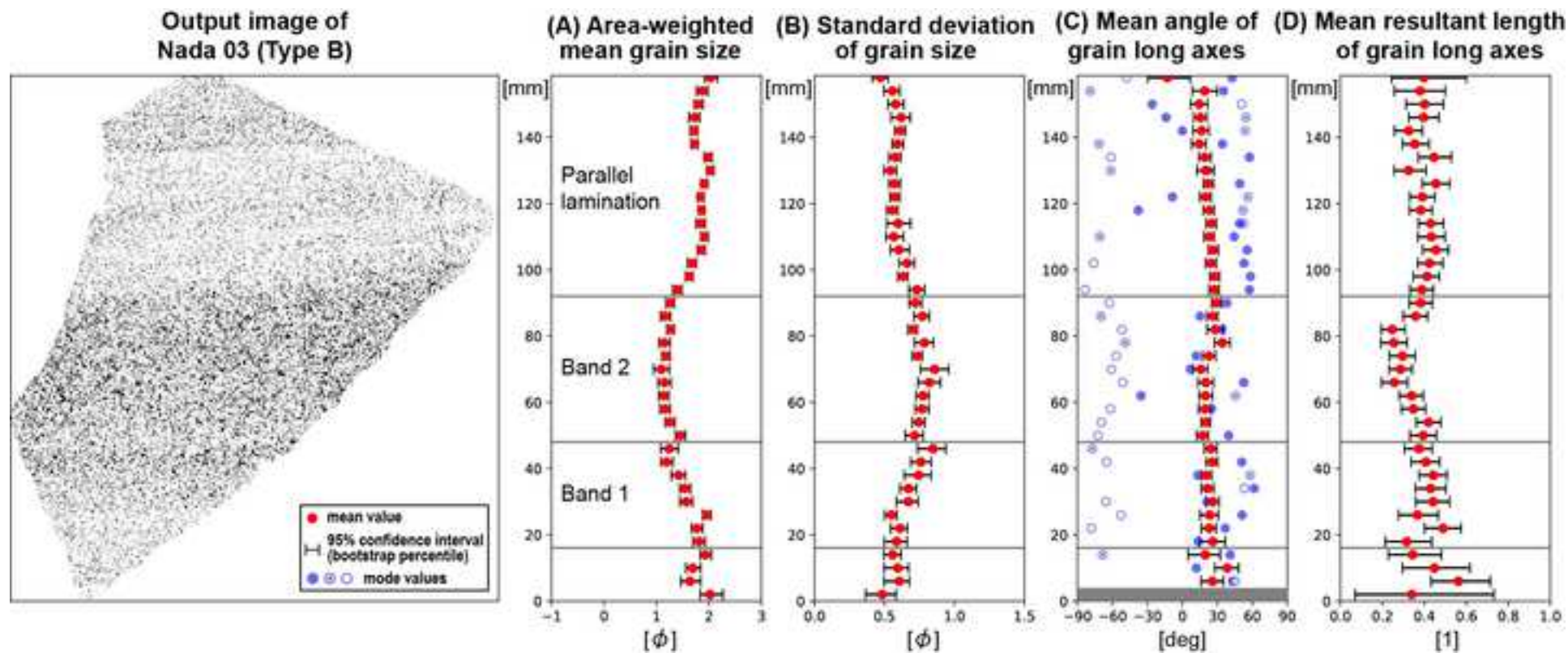
Facies	Descriptions	Interpretations
I	 Alternating beds of thin sandstones and mudstones Sandstone: 0.1–0.6 m thick, massive or normal-grading, showing parallel laminations, or SS Mudstone: 0.1–0.4 m thick, massive	Interdistributary channels of submarine-fan lobes deposited from high-concentration turbidity currents and interbedded with hemipelagites
II	 Sandstone-dominated alternating beds of sandstone, conglomerate, and mudstone Conglomerate: 0.1–0.6 m thick, massive or normal-grading Sandstone: 0.1–0.6 m thick, massive, normal-grading, or SS Mudstone: 0.1–0.4 m thick, massive	Proximal parts of submarine-fan lobes deposited from high-concentration turbidity currents
III	 Pebbly conglomerates with sandstone beds Conglomerate: 2.0 m thick, massive or normal-grading, including mud clasts Sandstone: 0.3–0.8 m thick, showing parallel laminations	Proximal regions of submarine lobes near channels deposited from high-concentration gravity flows

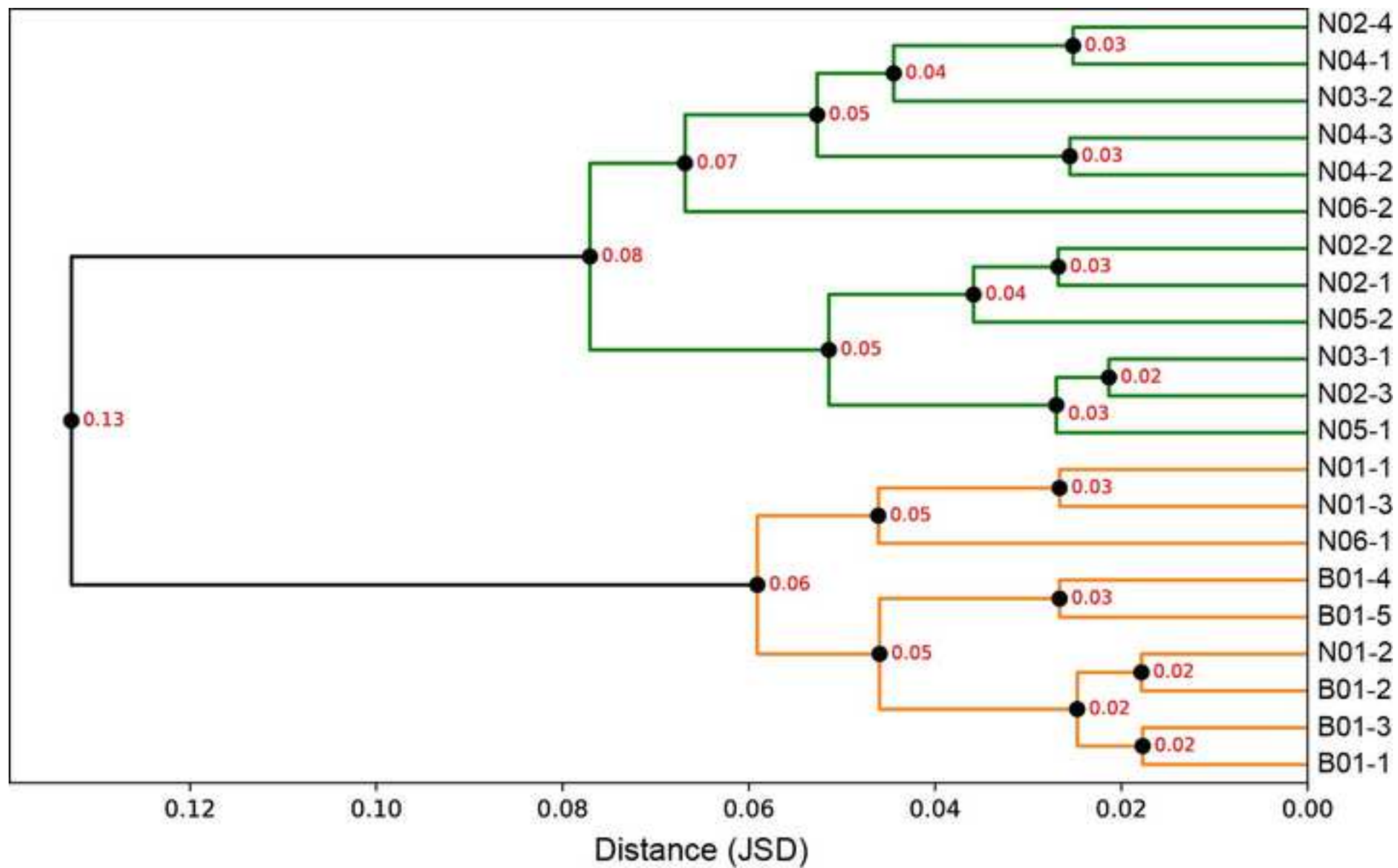


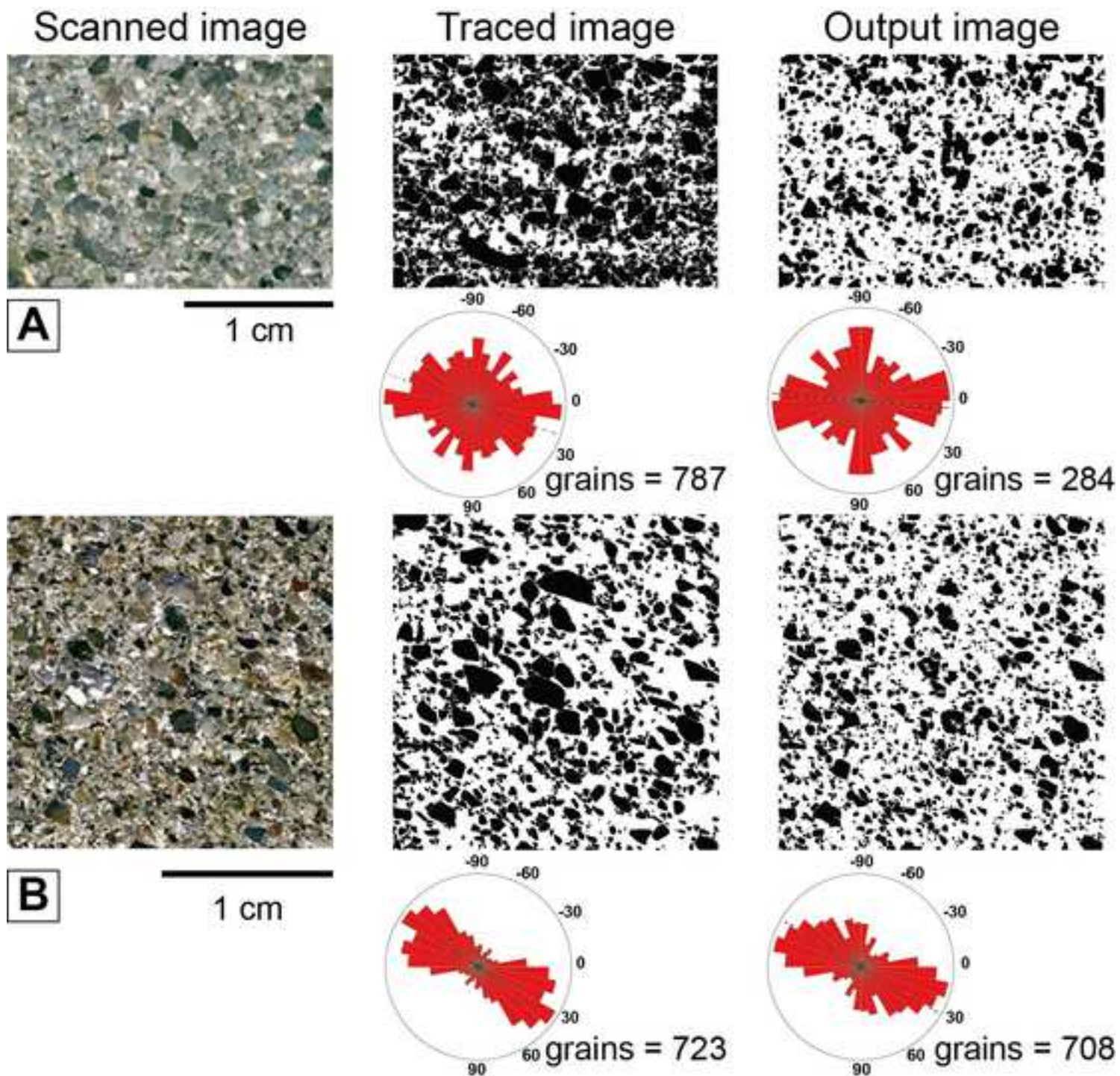


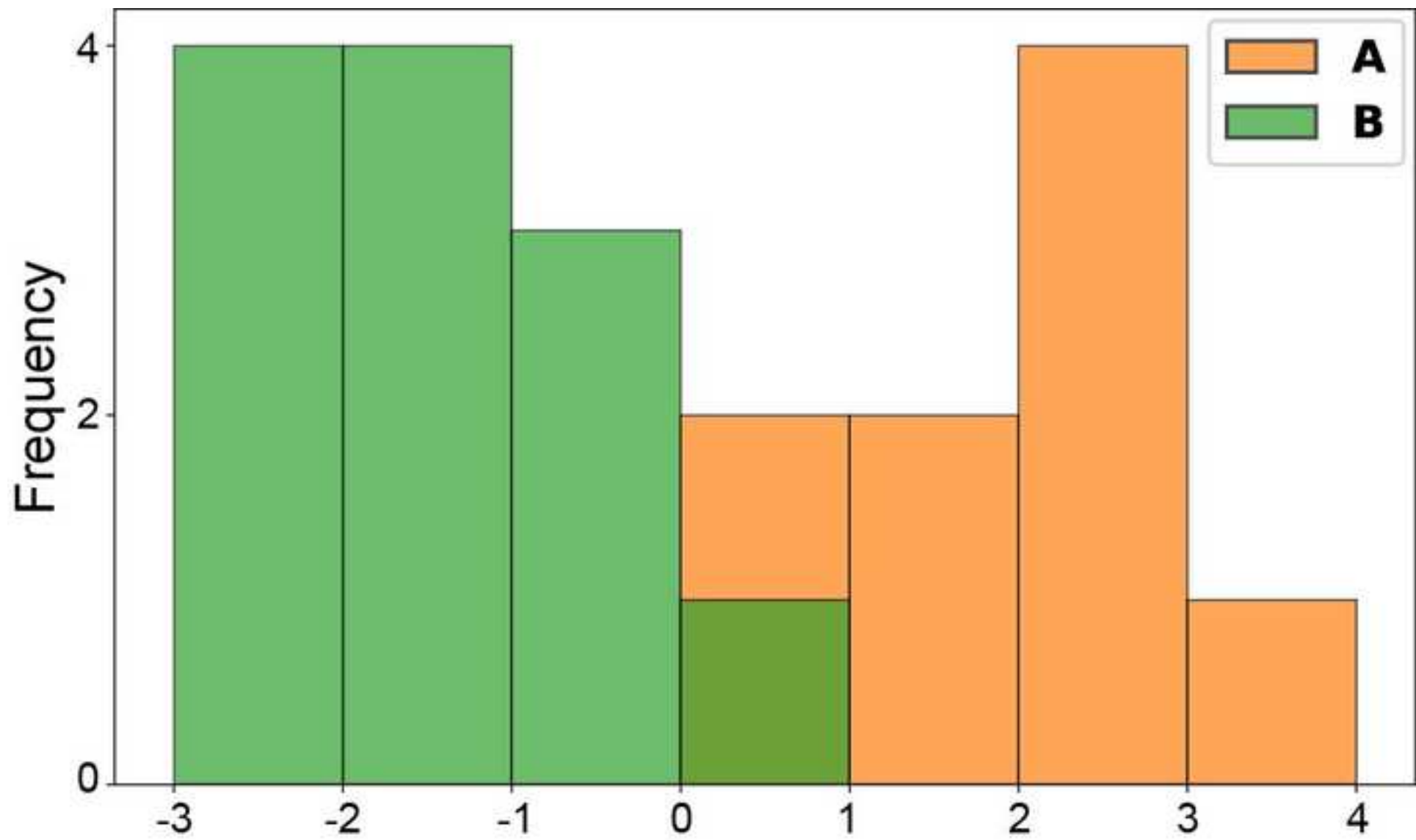


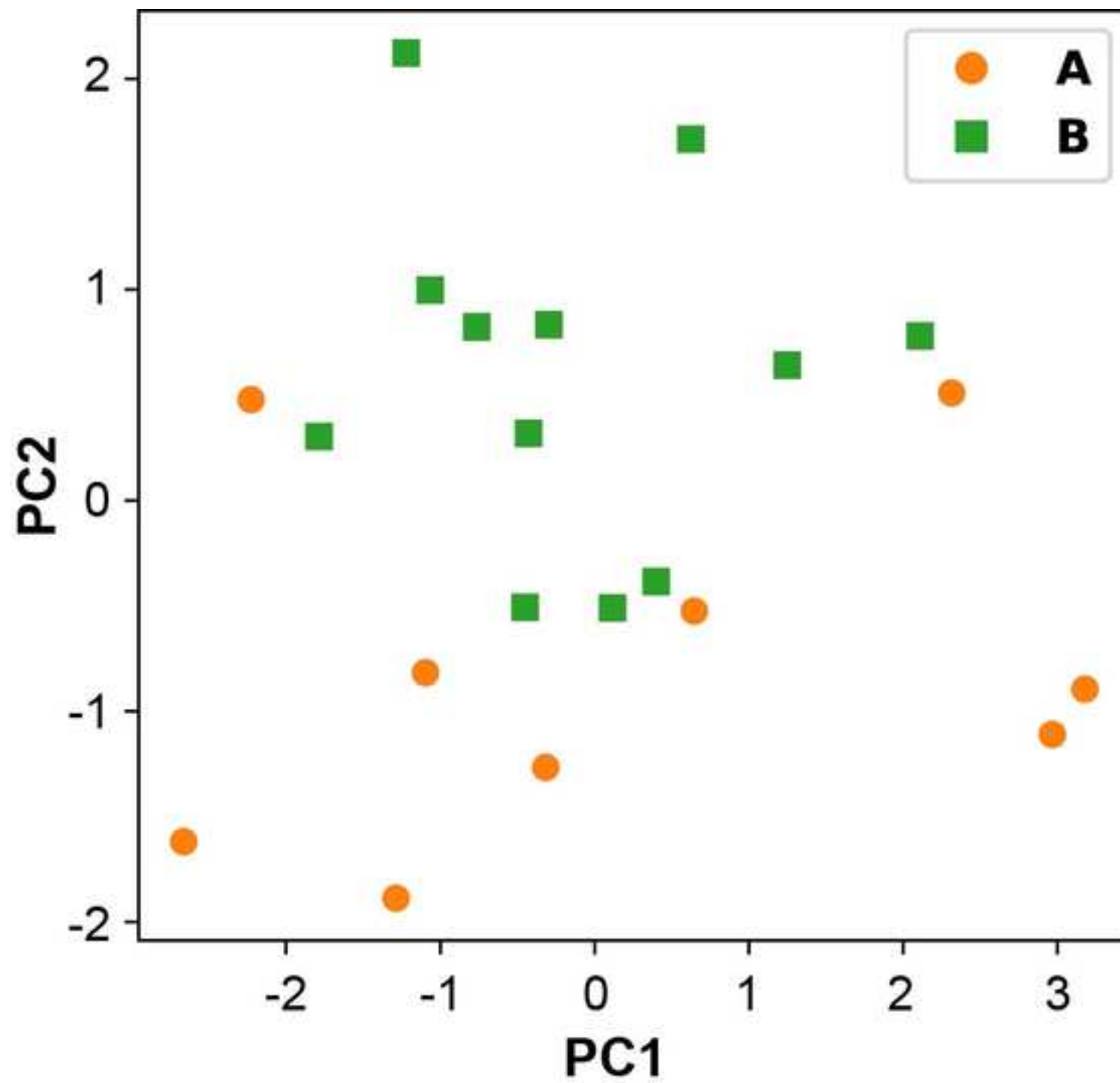












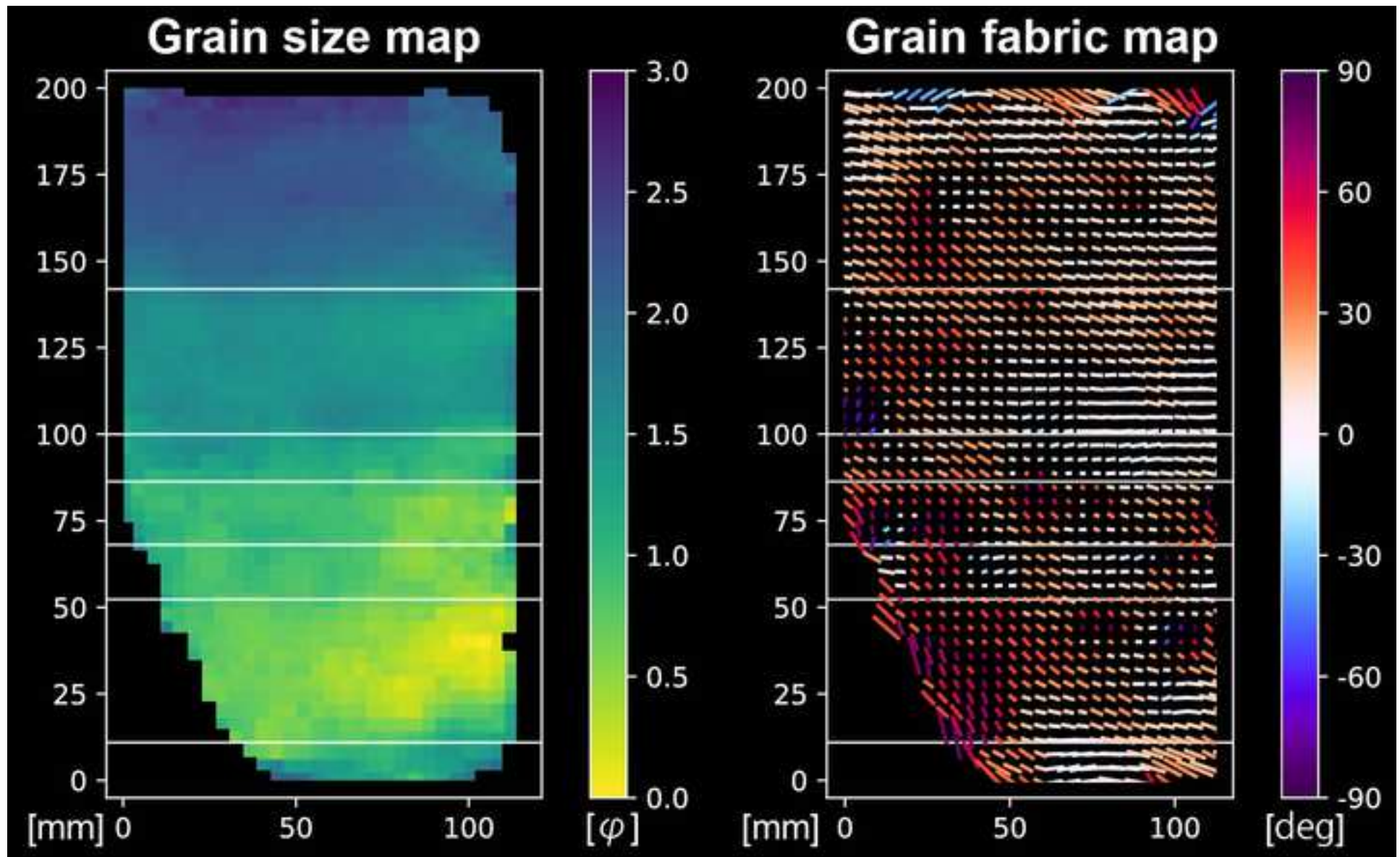


TABLE 1.--- Results of the statistical analysis of grain data. Statistical parameters were calculated for each band i

Sample	Type	Area-Weighted Mean Grain Size [phi]	Standard Deviation of Grain Size [phi]	Mean Angle of Grain Long Axes [deg]	Mean Resultant Length of Grain Long Axes [1]	Standard Deviation of Vertical Variation in Mean Grain Size [phi]
B01-1	A	0.49	0.89	30.41	0.10	0.12
B01-2	A	0.78	0.90	17.11	0.10	0.10
B01-3	A	0.80	0.87	33.84	0.08	0.04
B01-4	A	1.16	0.84	8.25	0.14	0.10
B01-5	A	1.45	0.68	15.07	0.14	0.07
N01-1	A	0.09	1.00	18.23	0.22	0.33
N01-2	A	-0.07	1.07	20.98	0.13	0.24
N01-3	A	0.24	0.92	17.89	0.23	0.22
N02-1	B	0.82	0.93	33.07	0.34	0.16
N02-2	B	1.00	0.82	30.12	0.38	0.11
N02-3	B	1.68	0.69	26.06	0.39	0.12
N02-4	B	1.58	0.72	19.25	0.35	0.21
N03-1	B	1.43	0.77	23.41	0.41	0.25
N03-2	B	1.20	0.77	22.98	0.32	0.09
N04-1	B	0.86	0.97	18.70	0.38	0.18
N04-2	B	1.05	0.91	13.79	0.32	0.17
N04-3	B	1.02	0.82	11.26	0.30	0.08
N05-1	B	1.24	0.95	25.83	0.43	0.12
N05-2	B	1.48	0.82	29.55	0.38	0.15
N06-1	A	1.37	0.74	28.79	0.18	0.04
N06-2	B	1.64	0.68	24.16	0.29	0.15

in the spaced-stratification samples, comprising a total of 21 bands from seven samples.

Standard Deviation of Lateral Variation in Mean Grain Size [phi]	Vertical Trend of Mean Grain Size	Thickness of the Band [mm]	Dip Test (p-value)	Watson's U ² Test (p-value)	LDA Score
0.30	-40.68	40	0.46	0.002	2.36
0.32	-31.48	16	1.00	0.036	2.18
0.23	-95.13	16	0.99	0.006	3.57
0.24	-31.39	12	1.00	0.001	0.99
0.07	-100.32	40	1.00	0.000	0.57
0.52	-28.81	36	0.99	0.254	2.22
0.20	-19.48	44	0.97	0.059	2.54
0.17	4.84	52	0.40	0.079	1.57
0.15	-56.53	64	0.97	0.000	-0.89
0.19	55.76	48	0.99	0.000	-1.43
0.15	37.34	36	1.00	0.000	-2.66
0.15	-42.77	32	0.33	0.000	-1.52
0.21	-32.83	32	0.99	0.001	-1.59
0.12	-38.94	44	0.82	0.000	-0.22
0.74	57.95	52	0.86	0.000	-2.92
0.27	-29.57	24	0.94	0.000	-0.14
0.88	-25.19	36	0.93	0.012	0.08
0.77	-4.76	36	0.42	0.000	-2.61
0.74	-53.36	48	0.35	0.000	-2.77
0.61	-143.34	24	0.99	0.000	1.80
0.58	-40.11	24	0.66	0.000	-1.13

TABLE 2.--- Coefficients of the linear-discriminant analysis (LDA) and eigenvectors of the principal-componen distinguishes between the two fabric types (Type A and Type B) on the basis of six descriptive statistics (1, 2, 5- underlying structure of the data and highlights the key features that differentiate the two types.

	Explained Variance	Area-Weighted Mean Grain Size [phi]	Standard Deviation of Grain Size [phi]	Standard Deviation of Vertical Variation	Standard Deviation of Lateral Variation in
LDA	-	-2.48	-0.93	-0.37	-0.17
Coefficients					
PC1	0.42	-0.52	0.54	0.45	0.02
PC2	0.18	0.40	-0.40	0.14	-0.27

it analysis (PCA). The LDA successfully
-8; Table 1). The PCA reveals the

Vertical Trend of Mean Grain Size	Thickness of the Band [mm]
−0.67	−0.76
0.34	0.34
0.55	0.53

FIGURES AND TABLES

FIG. 1.---Location map of the study area. A, B) Distribution of the Izumi Group (modified after Kikuchi and Kotake (2013)). C) Geologic map of the Bandodani Formation in the northeastern part of Naruto City, Tokushima Prefecture (modified after Makimoto et al. (1995)). D) Geologic map of the Nada Formation in the southeastern part of Awaji Island, Hyogo Prefecture (modified after Makimoto et al. (1995)).

FIG. 2.---Sedimentary columns of the study area. A) Columnar sections of the Bandodani Formation in the Aboshijima area. B) Columnar sections of the Nada Formation in the southeastern part of Awaji Island. Numbers beside the columns correspond to the sedimentary facies. Abbreviations: slt, siltstone; vfs, very fine sandstone; fs, fine sandstone; ms, medium sandstone; cs, coarse sandstone; vcs, very coarse sandstone; gr, granule; pb, pebble.

FIG. 3.---Examples of scanned cross-sectional images of sandstone samples with spaced stratification. A) Bandodani01 from the Bandodani Formation. This sample contains five inversely graded bands (Bands 1–5) and an overlying parallel-laminated interval. B) Nada03 from the Nada Formation. This sample contains two inversely graded bands (Bands 1, 2) and an overlying structureless interval.

FIG. 4.---Architecture of the CNN model used in this study. The left panel represents the encoder, and the right panel represents the decoder of the U-Net architecture.

FIG. 5.--- Examples of training datasets used for the CNN-based image segmentation model. A) Scanned color images of sandstone samples from the Izumi Group. B) Manually traced grayscale images in which grain areas are shown in black and matrix areas in white.

FIG. 6.--- Three types of sedimentary facies identified in the study area. Facies I consists of alternating mudstone and thin, fine-grained sandstone beds. Facies II comprises alternating thick, coarse-grained sandstone beds and sandy conglomerate beds. Facies III consists of very thick, pebbly conglomerate beds overlain by parallel-laminated sandstone beds.

FIG. 7.--- Photographs of outcrops in the study area. A) Facies I in the Nada Formation. B) Facies II in the Bandodani Formation. C) Facies II in the Nada Formation. D) Facies III in the Nada Formation. E) Spaced stratification (Bandodani01) observed in a sandstone bed of Facies II (Part B) in the Bandodani Formation. F) Spaced stratification (Nada01) observed in a sandstone bed of Facies II (Part C) in the Nada Formation. Scale bar in each photo = 1 m.

FIG. 8.--- A–C) An example of test datasets of the trained CNN model and D, E) results of accuracy verification for the trained model using sandstone samples from the Nada and Bandodani formations. A) Scanned color images of sandstone samples from the Bandodani and Nada formations. B) Manually traced grayscale images in which grain areas are shown in black and matrix areas in white. C) Output images of the CNN model, which automatically distinguishes grain and matrix regions. D, E) In both graphs, the horizontal axis represents the mean values of grains in the manually traced images (ground truth), and the vertical axis represents the corresponding mean values in the CNN model outputs. Error bars indicate 95% confidence intervals calculated by bootstrapping with 1,000 resamples. A total of 10 test images were used for accuracy validation. D) Scatter plot comparing mean grain size between the manually traced images and the CNN model outputs for each sample. E) Scatter plot comparing mean grain orientation between the manually traced images and the CNN model outputs for each sample.

FIG. 9.--- Examples of grain-size distributions and imbrication-angle distributions for each fabric type. A) Grain-size distributions of Bands 1 and 2 in Bandodani01 (Type A fabric) and Bands 1 and 2 in Nada03 (Type B fabric). The unimodality of all distributions was statistically confirmed by the Dip Test (Table 1). B) Imbrication and orientation-angle distributions of elongated grains (aspect ratio > 1.5) in the same bands. Type A fabric (Bandodani01) shows bimodal distributions, whereas Type B fabric (Nada03) shows unimodal

distributions. Strong peaks are observed in the orientation angle distributions of the horizontal planes, and these peaks align with the direction of the groove cast.

FIG. 10.--- Output from the CNN model for the cross-sectional scanned image of Bandodani01 (Fig. 3A). This spaced-stratification sample contains five inversely graded bands (Bands 1–5) and an overlying parallel-laminated interval. Thin gray lines on the images and graphs indicate the boundaries between individual bands. Note that in cases where an internal erosional surface is inclined (e.g., between Bands 3 and 4 in this figure), the characteristics of grains above and below the erosional surface may be mixed; therefore, these zones were excluded from the analysis. Vertical variations in grain parameters calculated from Bandodani01 are shown in Parts A–D: A) area-weighted mean grain size, B) standard deviation of area-weighted mean grain size, C) mean imbrication angle of grain long axes relative to the paleocurrent direction, and D) mean resultant length of the imbrication angles. These graphs correspond to the height of the cross-sectional image along the vertical axis and to the parameter values along the horizontal axis. Red dots represent mean values for grains in each 4 mm-high interval (calculated with a 4-mm moving step), and black bars indicate 95% confidence intervals based on the bootstrap method. Blue dots represent mode values estimated using a two-component von Mises mixture distribution. Dots indicate values where the mixture ratio of the two components is 50% or higher. Eye-like dots indicate values between 40 and 50%. Blue circles indicate values between 30 and 40%. Components below 30% are not plotted. Gray-shaded areas overlying some mean values and error bars in Part C indicate intervals where the null hypothesis of no preferred orientation in the imbrication-angle distribution could not be rejected at the 5% significance level according to the Rayleigh Test (Rayleigh 1880).

FIG. 11.--- Output from the CNN model for the cross-sectional scanned image of Nada03 (Fig. 3B). This spaced-stratification sample contains two inversely graded bands (Bands 1, 2). Vertical variations in grain parameters were calculated from Nada03.

FIG. 12.--- Results of hierarchical-clustering analysis based on the Jensen-Shannon divergence (JSD) of imbrication-angle distributions. The JSD was calculated from the kernel density estimates of imbrication-angle distributions for elongated grains (aspect ratio > 1.5) in each spaced-stratification band. The dendrogram illustrates the similarity in imbrication-angle distributions among the bands. Red numbers at the branching points indicate distances between clusters, where smaller values represent higher similarity in grain fabric. Sample names on the right side of the dendrogram are abbreviated as B for Bandodani and N for Nada. Samples Bandodani01 and Nada01 are grouped together, whereas samples Nada02 and Nada03 form the other cluster.

FIG.13.--- Comparison of imbrication-angle distributions obtained from manually traced images and CNN model outputs to verify two types of fabric. A) Examples of test images show bimodal distributions, Type A fabric, of imbrication angles in both the manually traced image and the CNN output. B) Examples of test images show unimodal distributions, Type B fabric, of imbrication angles in both the manually traced image and the CNN output.

FIG. 14.--- The result of the linear-discriminant analysis (LDA). The two fabric types (Type A and Type B) are clearly distinguished in the LDA space on the basis of six descriptive statistics (1, 2, 5–8; Table 1). The linear discriminant function classifies the bands with an accuracy of 100%. The coefficients of the linear discriminant function are listed in Table 2.

FIG. 15.--- The result of the principal-component analysis (PCA). The six descriptive statistics (1, 2, 5–8; Table 2) except for the imbrication angle and mean resultant length were used for the analysis. Samples with smaller PC1 values tend to be classified as Type A, while samples with larger PC1 values tend to be classified as Type B. The eigenvectors of PC1 and PC2 are listed in Table 2.

FIG. 16.--- Grain-size map and fabric (imbrication) map of the Bandodani01. The left graph visualizes the grain-size distribution, and the color of this map indicates the grain size.

The right graph visualizes the distributions of imbrication angle and mean resultant length. The color of this map indicates the imbrication angle, and the line length indicates the mean resultant length. These grain-distributional data are the mean value when the circle with a radius of 4 mm is moved at 4 mm intervals. This spaced-stratification sample has five inversely graded bands (Bands 1–5).

TABLE 1.--- Results of the statistical analysis of grain data.

Statistical parameters were calculated for each band in the spaced-stratification samples, comprising a total of 21 bands from four samples.

TABLE 2.--- Coefficients of the linear-discriminant analysis (LDA) and eigenvectors of the principal-component analysis (PCA).

The LDA successfully distinguishes between the two fabric types (Type A and Type B) on the basis of six descriptive statistics (1, 2, 5–8; Table 1). The PCA reveals the underlying structure of the data and highlights the key features that differentiate the two types.