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'Stratigraphically Homogeneous Zones': automated construction and restitution procedure for engineering geology use

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ABSTRACT
This study presents an automated method for the construction and spatialization of stratigraphic columns, facilitating the creation of maps of Stratigraphically Homogeneous Zones (SHZ). This approach integrates GIS tools with custom Python scripts, streamlining the manual process traditionally used in Seismic Microzonation (SM) studies according to Italian standards. Our method allows for rapid, scalable processing and provides a detailed geological model of near-surface stratigraphy, essential for land management and seismic risk assessment. We employed our scripts to automatically produce the map of SHZ in the test area of Cariati (Northern Calabria), demonstrating their effectiveness by accurately replicating and extending the manually-derived stratigraphic columns. Additionally, this procedure enhances accessibility to geological data by enabling subsurface insights through spatialized 1D stratigraphic information, while preserving the simplicity of 2D visualization. This advancement holds promise for broader applications in territorial planning and infrastructure development, supporting informed decision-making in various fields of geoscience and engineering.

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Northern Calabria; Python scripts; Engineering-Geological Units; Stratigraphically Homogeneous Zones; Seismic Microzonation; GIS Automation

Key policy highlights

- **Automation and Integration**: The study introduces an automated method that integrates GIS tools with custom Python scripts, enhancing the traditional manual process of creation of maps of Stratigraphically Homogeneous Zones (SHZ), required by Seismic Microzonation (SM) approaches.
- **Rapid and Scalable Processing**: The new method allows for rapid and scalable processing of stratigraphic data, providing a detailed geological model of near-surface stratigraphy.
- **Method Evaluation**: The method was successfully applied in the test area of Cariati (Northern Calabria), demonstrating its effectiveness by accurately replicating and extending manually-derived stratigraphic columns.
- **Broader Applications**: This method supports informed decision-making in territorial planning and infrastructure development, with potential applications in various fields of geoscience and engineering, such as land management and seismic risk assessment.

1. Introduction

The division of the territory into areas characterized by homogeneous near-surface stratigraphy, called 'Stratigraphically Homogeneous Zones' (SHZ), is a mandatory practice in the official Italian standards of Seismic Microzonation (SM) studies (SM Working Group, 2008). According to Italian standards, the construction of the SHZ map is the tool for modeling and spatializing local seismic effects. The SHZ map is derived from the elaboration of a generative geological map, which involves first the reconstruction of all the possible configurations of the near-surface stratigraphy, and then contouring the areas associated with each of them.

Apart from this specific use, the SHZ map represents an alternative way of picturing the geology of a region, providing an easy-to-use tool for non-geologists to read the variability, in the subsurface, of the stratigraphic layering. In this perspective, the construction of SHZ maps may have wider applications in many scientific areas of territory management and protection. These fields need accuracy in defining subsurface geological models, crucial for the reliability of the outcomes and predictions.

Here we illustrate an automated procedure that reproduces the steps for the construction and restitution of a SHZ map, usually manually operated during the SM studies. Our method is developed

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in the frame of the Italian National PRIN project 'Mapping SEismic site effects at REgional and NAtional scale – SERENA'. The proposed procedure restitutes, starting from a vectorial geological map, all the possible 1D stratigraphic logs, successively spatialized by the cells of a regularly-spaced grid. In particular, we employ an integrated approach combining a supervised procedure developed in a GIS environment and a standalone script package. We apply the proposed codes on the geological map of the Territorial Context of Cariati (Calabria, southern Italy), where Cesarano et al. (2022) already manually derived a comprehensive matrix of all the possible stratigraphic columns.

We validate the method by comparing our restituted stratigraphic logs with the manually-derived ones by Cesarano et al. (2022). Then, the spatialization step is completed once one among the possible restituted stratigraphic columns has been assigned to each cell of the adopted grid. The mosaic of the SHZ, depicted in the final output main map, derives from the final contouring of cells with the same 1D stratigraphic log.

2. Methods

Our procedure concerns the automatic identification and spatialization of stratigraphic columns of a study area, starting from a geological map. The goals have been achieved through the development of both standalone and QGIS-integrated Python scripts. Open-source Python libraries such as *numpy* and *scipy* (Harris et al., 2020; Virtanen et al., 2020) have been employed to optimize the performance of the scripts with faster array computation. The main final output is a raster map in which each pixel holds a full stratigraphic column, identified by a unique integer.

Regardless the specific case of the Cariati area, the required inputs of our procedure consists of: a) a raster geothematic map (e.g. geological map, lithological map, engineering-geological map), appropriately categorized following the geometric position of the outcropping units ('pos' attribute, see Figure 1A) and b) a raster thickness map with the same extension and resolution of the geothematic map, which contains the estimated thickness of units outcropping in each pixel ('thi' attribute, see Figure 1B). Optionally, a shapefile version of the geothematic map, populated

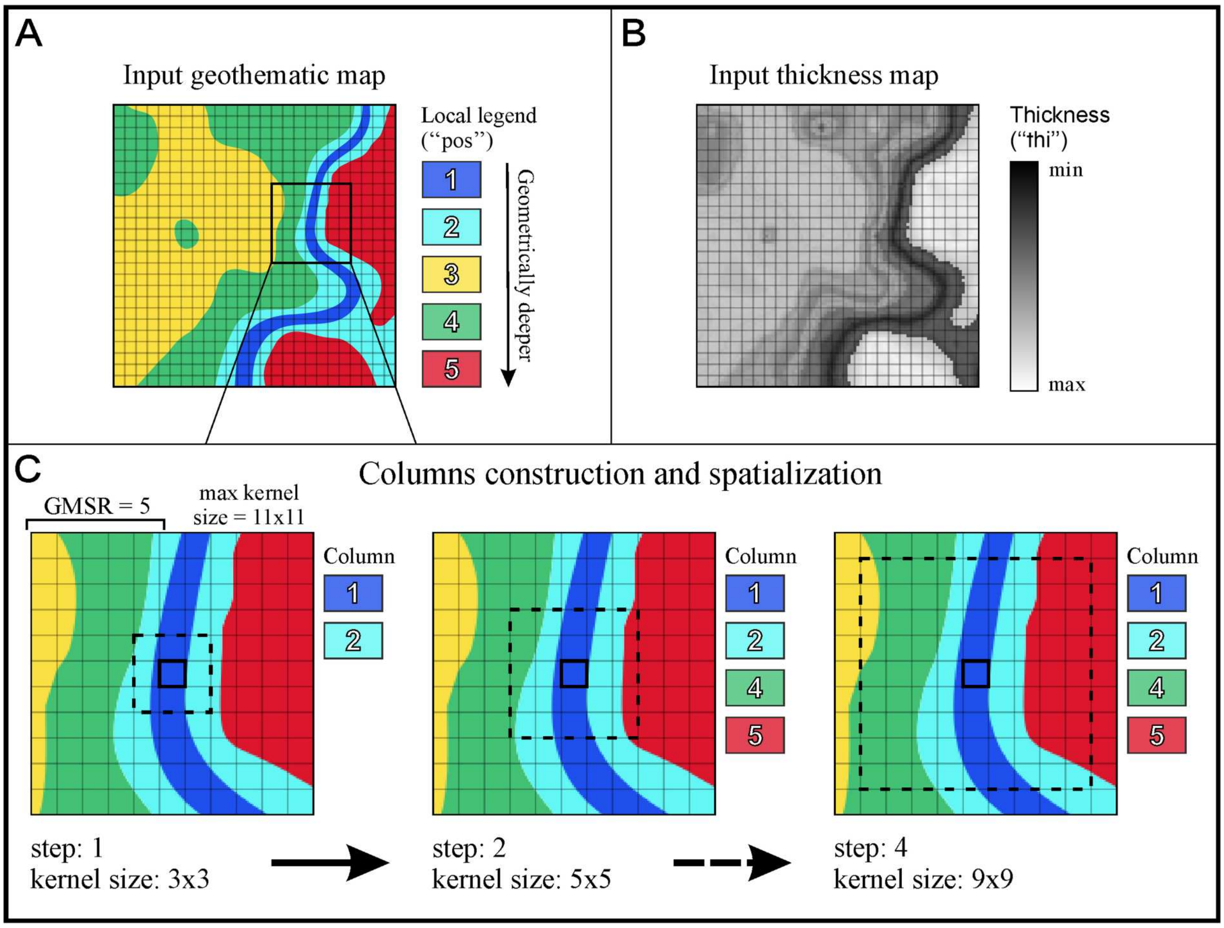


Figure 1. Schematic representation of (A) input raster geothematic map, reclassified following the geometric position order of outcropping units ('pos' attribute); (B) input raster thickness map, indicating the estimated thickness of outcropping units in each pixel ('thi' attribute) and (C) automated pixel-wise construction and spatialization of stratigraphies. In step 4, note how the procedure skips the unit with 'pos' = 3 because the lowermost unit of the constructed log has a deeper 'pos' value (i.e. 5).

with both ‘pos’ and ‘thi’ fields, can be provided for a more user-controlled reconstruction of the stratigraphic columns (QGIS-integrated, supervised approach; see subsection 2.3).

The ‘pos’ attribute, preliminary defined by users according to the local stratigraphy and geometries of the studied area, is crucial for the categorization of the input geothematic map. The ‘pos’ attribute is defined as a non-negative integer increasing with the deeper geometric position of the outcropping units. In other words, for n-total outcropping units, we categorize the uppermost unit as 1 and the lowermost unit as n, thus quantifying the relative vertical position of each unit with respect to the others. Ultimately, it can be leveraged by users to merge several units together or, oppositely, to split a single unit in two or more sub-units. This is particularly useful in case of geological complexities due to, for example, inverted stratigraphies, thrust tectonics, etc. The ‘pos’ attribute is, therefore, one of the major constraints of our scripts, with a huge impact on the final output.

Another user-defined constraint that significantly influences the scripts’ behavior is the *global maximum search radius* (GMSR). This integer parameter sets the area around a pixel, within which information of adjacent units (e.g. ‘pos’, ‘thi’ attributes) is gathered to build a vertical stratigraphic column. The GMSR is expressed in pixel units, but it can be easily translated into map units’ distance by multiplying it to the input map cell size.

Finally, an additional user-controlled parameter that plays a central role in the final result is the *column interruption criterion* (CIC). The CIC determines the logic employed by the scripts to determine when the piling of units in a stratigraphic column must be interrupted. Users can choose among five different provided criteria, which are discussed in detail in subsection 2.2.

The level of detail and accuracy of the output produced by the proposed procedure are inherently dependent on the scale and resolution of the input raster geothematic data. While the procedure itself is scale-independent and adimensional, operating consistently across different spatial contexts, the granularity of the resulting stratigraphic interpretation is directly tied to the input map’s level of detail. Specific advantages or limitations of the proposed method primarily concern the level of detail that the user expects to achieve in relation with the scale and resolution provided by the input map. For highly detailed stratigraphic reconstructions, larger-scale maps (often corresponding to smaller areas) are typically required. Conversely, broader overviews are more effectively achieved with small-scale maps covering larger areas.

2.1. Main algorithm

Our scripts identify and spatialize the stratigraphic columns in a pixel-based fashion by employing a 2D squared sliding window (kernel) with size equal to $(\text{GMSR} \cdot 2) + 1$ (see Figure 1C). The kernel is iteratively centered on each pixel of the input geothematic map; the first unit of the output stratigraphic column is always the one outcropping at the central pixel. Then, a custom algorithm identifies the adjacent pixels described with a bigger ‘pos’ attribute (i.e. units geometrically lower than the current deepest unit of the column) and appends them to the column. In this way, the identification and the spatialization processes are carried out at the same time. The obtained stratigraphic columns are encoded with a progressive non-negative integer ID. Columns that share the same sequence of units are encoded with the same ID.

Even if the sliding window already frames all the pixels falling within the GMSR, the use of dynamic binary masks allows the algorithm to progressively sift pixels located farther and farther from the centered pixel. When the CIC is satisfied (see subsection 2.2), this procedure is interrupted and the stratigraphic column is returned. The associated confidence value (C) is inversely proportional to the actual radius (R) that was required to meet the CIC:

$$C = 1 - R/(GMSR + 1)$$

If the CIC is never met, the algorithm will still output the constructed column with a confidence value of 0.

2.2. Column interruption criteria (CIC)

In order to provide the tool with more versatility, we integrated five different criteria for interrupting the construction of stratigraphic columns. Users can select one of those depending on their preferences or needs:

- *Thickness*. The column is interrupted when an arbitrary minimum cumulative thickness is reached. The thickness value of each processed unit is accessed from the thickness raster.
- *Substrate*. The column is interrupted when a substrate unit is reached. The definition of substrate unit depends on the input data and, especially, on the operator’s specific objectives. This offers greater flexibility and provides the operator with more control over the procedure. Therefore, users must define which units are to be considered as cover and which ones are to be considered as substrates. If the first unit of the column (i.e., the outcropping unit) is already a substrate unit, the column is interrupted immediately with the highest confidence value (= 1). For a different behavior, *Second Substrate type 1* or *type 2* can be used (see below).

- *Second Substrate (type 1)*. As with *Substrate*, but if the outcropping unit is already a substrate, the *Thickness* criterion is applied until a second, deeper substrate unit is found. The column will still be returned immediately if the outcropping unit is as thick or thicker than the required minimum cumulative thickness.
- *Second Substrate (type 2)*. As with *Substrate*, but if the outcropping unit is already a substrate, the algorithm continues to search for a second, deeper substrate unit for an arbitrary local maximum search radius (LMSR) that must be smaller or equal to the GMSR. If the LMSR is set to 0, this criterion coincides with the *Substrate* one.
- *Fitting*. This criterion completely overhauls the identification process of the stratigraphic columns. Instead of relying on a full unsupervised approach, the columns construction is constrained by a list of pre-determined, validated columns types (supervised approach). The column is returned if it perfectly fits one and only one of the valid columns, which are generated through a QGIS-based Python script (see subsection 2.3 for details).

Regardless of the chosen criterion, the column construction procedure is always interrupted if the CIC is not satisfied after all the pixels included within the GMSR have been processed.

2.3. Fitting algorithm, supervised method

The fitting code is a Python function designed to operate within the QGIS software environment. It implements a supervised procedure to progressively construct stratigraphies in individual steps. This method allows us to check at each step the stratigraphic columns being constructed. Input data for the algorithm derive from a shapefile that represents the digitized geothematic map of the study area. This polygonal file maps each unit outcropping in the analyzed area. The attributes table associated with the shapefile contains for each polygon essential information for the stratigraphic reconstruction. In more details, the 'pos' attribute, indicating the geometric position, is crucial for the ordering of units in the algorithm as it defines the sequence in which they appear in the subsurface model, reflecting their real stratigraphic disposition. The 'thi' attribute, indicating thickness, allows defining the vertical extent of the analysis. This value is progressively employed to calculate a cumulative thickness when multiple units are combined, stopping the iteration when the predetermined thickness is reached.

The first analysis step creates a new output level where the outcropping units constitute the first layer of the stratigraphic column under construction. Then, the script examines each polygon to determine its interaction with adjacent polygons. For each polygon, it checks for the presence of neighbors it is in contact with, preferring those in a higher 'pos' vertical position. When such a neighbor is present, it is added to the column as a lower layer, and new features are created, that include the 'pos' of the polygons and the sum of the thicknesses ('tot_thi') of the original polygons (Figure 2B). If a polygon has no direct neighbors in a lower geometric position, a new search is conducted in the area around the polygon, whose extent can be set by the user (Figure 2A), adopting a similar approach in combining geometries and in calculating combined thicknesses.

In the following analysis steps, the algorithm further develops the stratigraphic sequence of the subsoil by adding layers according to the vertical geometric positions ('pos') and thicknesses ('thi') of units. Each step incorporates a new layer, adding an extra segment to the three-dimensional stratigraphic model, and progresses through the subsequent key steps:

- Initialize the new analysis level. At each iteration phase, generate a new level populated with the attributes from the preceding step and new current-phase-specific attributes, such as the refreshed cumulative thickness of the layers ('tot_thi').
- Total thickness control. The algorithm monitors the cumulative thickness ('tot_thi') of the layers referenced in the last analysis step. If the total thickness meets or exceeds a specific predetermined limit, no additional layers will be added in the current step.
- Examination of current features. The algorithm examines for each column the last stratigraphic layer inserted in the previous step, comparing it with the polygons in the original level (input geothematic map). Using the 'pos' attribute, it defines the stratigraphic interactions and identifies relationships of overlap, contact, and vertical succession between units to determine the next layer to add to the stratigraphic column.
- Insertion of new layer and updating of thicknesses. If two units overlap, their thicknesses ('thi') are aggregated to achieve the cumulative thickness, and the new layer is added to the stratigraphic sequence (Figure 2C).
- Iterate for the next step. Once the current iteration is completed, a new analysis step is initiated, and the process repeats, gradually adding layers to the stratigraphic sequence and extending the subsoil model.

The 'pos' attribute guides the stratigraphic logic of the algorithm, ensuring that the reconstructed three-dimensional structure faithfully reflects the

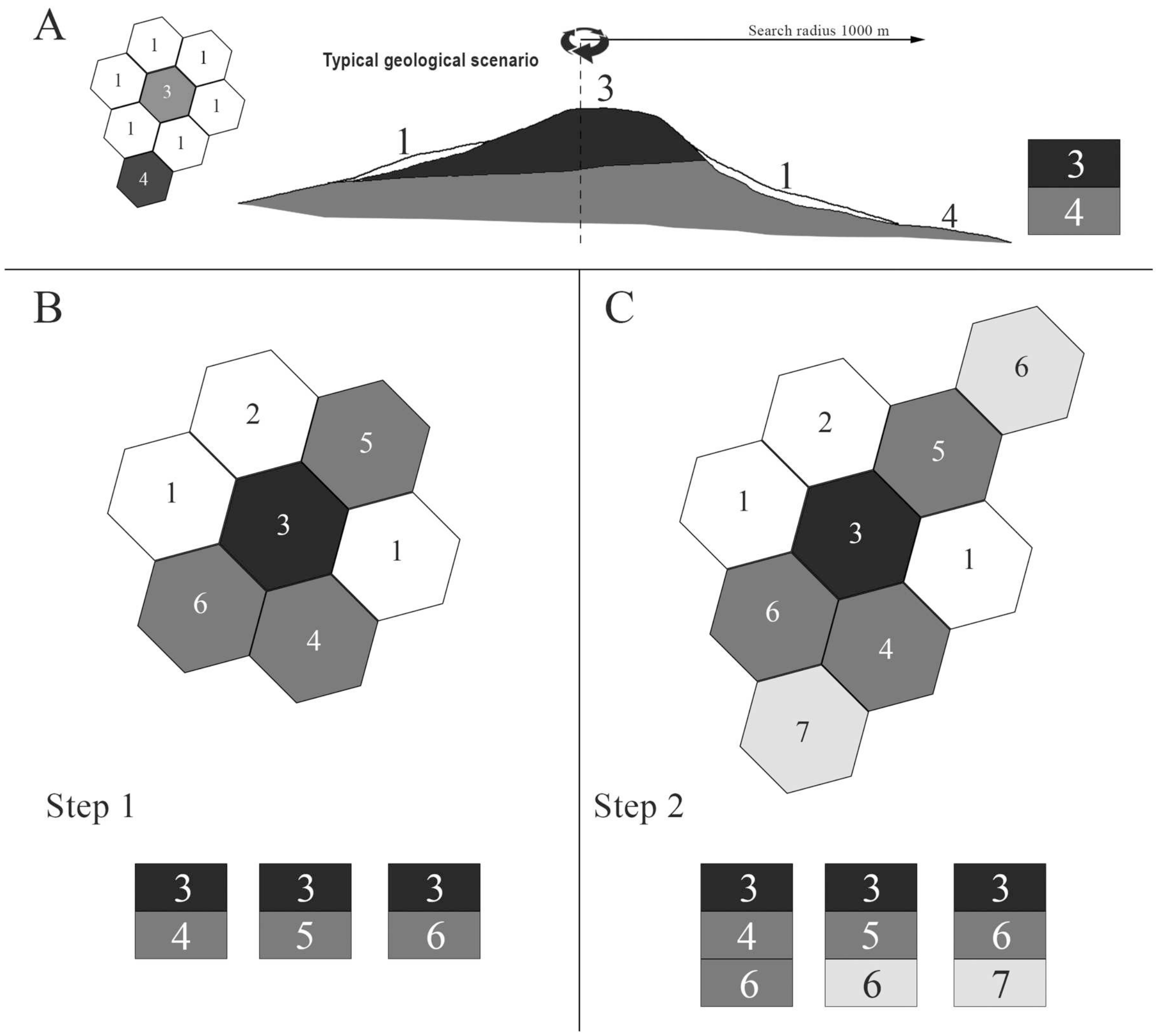


Figure 2. (A) Layer search logic in cases where the unit under examination is surrounded by units in a lower geometric position; Example of constructing stratigraphic columns for unit in 'pos' 3; (B) Step 1; (C) Step 2.

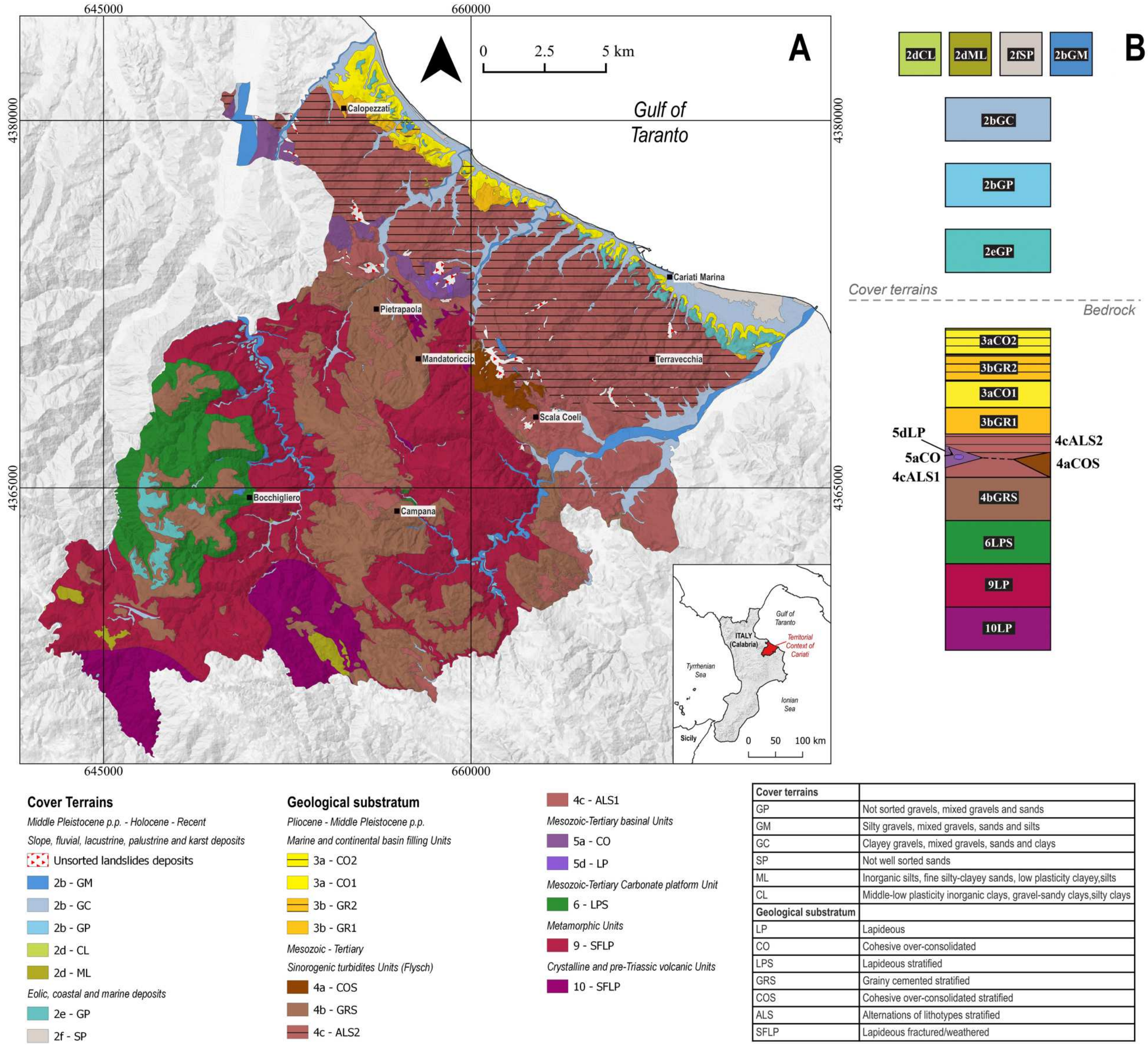
stratigraphic relationships observed or inferred for the study area. The resulting stratigraphic columns can then be used to drive the main algorithm towards their pixel-based search and spatialization in the input map space, using the *Fitting* CIC (see subsection 2.2).

3. Geological input data

The geological dataset, utilized to test the procedure, refers to the Cariati Territorial Context (Regione Calabria DGR 498/2019), in southern Italy. This ~428 km^2 wide area was selected as a case-study by Cesarano et al. (2022) that first compiled a multiscale geothematic map for seismic zonation purposes, using as cartographic base the 1:25,000 scale CASMEZ Geological Map (Cassa per il Mezzogiorno, 1967). The Authors first codified the lithostratigraphic units, at national and regional scale, in terms of Engineering-Geological Units (EGUs), according to the Seismic Microzonation (SM) guidelines and standard (SM Working Group, 2008; Technical Commission for Seismic Microzonation, 2020), assigning them alternatively to the geological bedrock or to the covers.

The study area is located along the Ionian side of northeastern Calabria (see inset in Figure 3A). A large part of the outcropping units consists of crystalline and metamorphic basement rocks, with their sedimentary covers spanning in age from Mesozoic to the Early Pleistocene. Unconformable Middle Pleistocene to Holocene marine and continental clastic deposits (e.g., marine terraces and fluvial and slope deposits) represent the cover terrains units. Following the SM guidelines and standard, the bedrock units have been grouped into four Engineering-Geological Groups (EGGs) (LP – Lapideous, GR – Grainy cemented, CO – Cohesive overconsolidated, AL – Alternations of lithotypes) further divided in EGUs on the base of the level of layering, fracturing and weathering. Similarly, the cover terrains have been classified into three EGGs (GX – gravels, SX – sands, CX – clays) and EGUs depending on the textural mixing and sorting (see Table 4 of Cesarano et al., 2022).

The vertical relationships between the described EGUs, shown in Figure 3B, represent the spatial and geometrical input data for our procedure.



Cover terrains	
GP	Not sorted gravels, mixed gravels and sands
GM	Silty gravels, mixed gravels, sands and silts
GC	Clayey gravels, mixed gravels, sands and clays
SP	Not well sorted sands
ML	Inorganic silts, fine silty-clayey sands, low plasticity clayey,silts
CL	Middle-low plasticity inorganic clays, gravel-sandy clays,silty clays
Geological substratum	
LP	Lapideous
CO	Cohesive over-consolidated
LPS	Lapideous stratified
GRS	Grainy cemented stratified
COS	Cohesive over-consolidated stratified
ALS	Alternations of lithotypes stratified
SFLP	Lapideous fractured/weathered

Figure 3. (A) Engineering-geological map of the Cariati Territorial Context. (B) Stratigraphic relationships between Engineering-Geological Units. (From Cesarano et al., 2022, modified).

4. Cariati case history and results

The application of the script to the EGUs reported in the Engineering-geological map of the Cariati Territorial Context restituted all their possible vertical 1D combinations at depth. Following the work presented in Cesarano et al. (2022), the EGUs were sorted by their geometric (stratigraphic and tectonic) stacking position ('pos' attribute); their thickness ('thi' attribute) was set according to the maximum values as reported in literature. The 'pos' and 'thi' attributes were used to generate the two input rasters required by our procedure, using a squared raster cell size of 10 m. This resolution was deemed appropriate to capture the smallest mappable features at the given input scale (i.e. 1:25,000), ensuring adequate preservation of the original geometries while maintaining reasonable computational performance.

We launched our scripts employing a GMSR of 1 km (100 pixels) and the *Second Substrate (type 2)* as criterion, with a LMSR of 500 m. The output data consist of all the automatically identified and spatialized vertical 1D combinations of the outcropping EGUs, which were compared to those manually obtained by Cesarano et al. (2022) and condensed in matrix form (see Figure 11 of Cesarano et al., 2022). Our procedure identified and spatialized 129 different stratigraphic columns, including 75 among the 80 columns predicted in the matrix by the previous Authors. The remaining 5 have been excluded because, even if possible, they have not been actually supported by the geometric relationships presented in the input geological map.

The automated procedure evidenced some new extra columns than the manually-obtained ones, mostly due to different rules adopted for the column construction. In particular, 28 additional columns refer to configurations including landslides or consisting of a single unit, not considered in the manually-derived matrix. The other new 21 automatically obtained columns, effectively, include valid configurations not detected by the previous manual approach. Each one of these extra stratigraphic columns was manually verified and validated against the input geological map to assess if geologically feasible, based on the spatial arrangement of the outcropping units.

The final output of the procedure (Map of Stratigraphically Homogeneous Zone in the Territorial Context of Cariati, Calabria, Southern Italy) is the restitution of a raster, with resolution of 10 × 10 m, whose single pixel is associated to one of the 129 columns, defining the near-surface vertical layering at that point. By contouring the adjacent pixels associated with the same column, we obtained the final puzzle of 'Stratigraphically Homogeneous Zones'. In the legend of the map, they are completely designed by the color and the number of the correlative stratigraphic columns. Columns are grouped by different tonalities of the same color, to represent the different subsoil configurations, starting from the same geological substratum units. In the map, only 4 (IDs 19, 20, 23, 24) out of 129 columns have a spatialization that locally contradicts the geometry between EGUs due to the entrenchment of cover units within different terms of the geological substratum.

The final map is like a mosaic whose single tile refers to an area with almost homogeneous subsoil layering, in terms of lithology and mechanical properties, and whose grain pictures the variability of the subsurface features. We can use this document as a re-classified geological map, adapted for multidisciplinary approaches requiring an easy-to-use tool for non-geologists. In addition, our methodology provides subsurface georeferenced punctual information about the different geological substratum units shown in the sketch map.

The produced cartographic output reflects the accuracy and level of detail inherent to the scale of the Engineering-Geological Map of the Cariati Territorial Context (i.e. 1:25,000). The representation scale of the map (i.e. for publication purposes) does not affect the underlying geological resolution.

5. Conclusions

We propose an automated, scale-independent procedure reproducing the intellectual workflow to obtain the near-surface subsoil layering from a geological map. The result is the zonation of the territory according to areas showing the same predicted 1D subsurface configuration, the so-called 'Stratigraphically Homogeneous Zones' (SHZ). The integration of GIS tools with custom-developed Python scripts has allowed for the effective automation of the construction and restitution process of the SHZ. This methodology represents a significant advancement in land management and protection, providing an accurate and detailed geological model essential for applications in territorial planning and seismic site effect assessment.

As a case study, we analyzed the Engineering-geological map of the Cariati Territorial Context following the work presented in Cesarano et al. (2022). The results show that our automated approach can more accurately replicate the stratigraphic columns manually predicted by Cesarano et al. (2022), with the additional advantages of a faster and more scalable data processing and automatic columns spatialization.

The restitution of the map at regional scale would provide a speditive method for bridging the smaller widespread areas studied in detail by MS analyses, according to the Italian standards for spatializing the local seismic effects. Hopefully, in the near future this map could have a wider application in other fields of territory management, providing an AI supported/validated elaboration and interpretation of geological maps.

Software

The raster datasets were generated using custom Python scripts (Python version: 3.8.17) specifically written for this purpose. The employed external Python libraries were *numpy* v.1.24.3 and *scipy* v.1.10.1. The maps were created using QGIS software v.3.28.15.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

The data that support the findings of this study are available from the corresponding author, Alberto D'Agostino, upon reasonable request.

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