

OBJECT-ORIENTED IMAGE ANALYSIS FOR THE IDENTIFICATION OF GEOLOGIC LINEAMENTS

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KEY WORDS: Remote Sensing, Geomorphology, Fuzzy Classification, Alevrada, Edge Detection, Faults, Hierarchical Segmentation

ABSTRACT:

In this work, a methodological framework employing image processing techniques has been developed and applied on a LANDSAT-ETM+ image of Alevrada, Greece. Pre-processing of the satellite image was followed by edge detection performed on band 5 of the ETM+ image in order to obtain proper input data to the lineament identification system. NDVI, PCA and ISODATA unsupervised classification were applied for the discrimination of the land cover classes. The input data layers to the lineament identification system included (1) an edge map from the *EDISON* algorithm, containing the edges to be classified, (2) the geologic layers derived from the pre-processing phase, (3) the initial ETM+ image and derived thematic products. Image segmentation was based on the multi-scale hierarchical segmentation algorithm for the extraction of primitive objects to be classified during the classification process. Six segmentation levels were created and their parameters were selected through a trial-and-error procedure. The design of the knowledgebase involved in the definition of classes / sub-classes of the scene, by spectral and geometric attributes, texture, spatial context and association on each segmentation level. Fuzzy membership functions and the Nearest Neighbor Classification were used for the assignment of primitive objects into the desired classes combining all participating levels of class hierarchy. The output result of the system was a classified lineament map containing the inherent geologic lineaments of the study area (faults) and the lineaments, which were not identified as faults (non-interest lineaments). From the classification stability map, it was inferred that there was a high degree of coincidence of the extracted results of the knowledge-based scheme and the tectonic map of the area.

1. INTRODUCTION

Geologic lineament mapping is very important in Engineering problem solving, especially for site selection for construction (dams, bridges, roads, etc), seismic and landslide risk assessment, mineral exploration, hot spring detection, hydrogeologic research, etc. (Sabins, 1997).

Several research aspects of geologic lineament mapping have been theoretically approached in parallel with the development of sophisticated automatic linear extraction techniques using Computer Vision algorithms. This need evolved because photointerpretation of geologic lineaments (e.g. faults, fractures and joints) is very subjective and highly dependent on the photointerpreter's skills, as well as the data quality and redundancy. It is also time-consuming and expensive, as it requires well-trained photointerpreters. Therefore, an effort towards automation of the lineament interpretation process is well justified.

Research efforts reported for the enhancement, semi-automatic or automatic lineament detection and extraction can be categorized as following.

1. Enhancement with the use of linear and non-linear spatial filters, such as directional gradients, Laplacian filters, Sobel and Prewitt operators (Morris, 1991, etc), as well as morphological filters (Tripathi et.al, 2000).

2. Semiautomatic and automatic lineament extraction, such as edge following, graph searching (Wang and Howarth, 1990), novel edge tracing algorithms (Segment Tracing Algorithm (STA)) (Koike et.al, 1995), etc.
3. Identification by optimal edge detectors (e.g. the algorithms of Canny (Canny, 1986), Rothwell (Rothwell et.al., 1994), and *EDISON* (Meer and Georgescu, 2001), etc) has provided quite promising results in terms of one-pixel thickness, efficient length and pixel connectivity (Argialas and Mavrantza, 2004).
4. Design of a knowledge-based system that could take into account the measurable information (length, aspect) of geologic lineaments (faults and drainage net segments) from a DEM (Morris, 1991), the design of an expert system exploiting the descriptive geologic information relative to lineaments, without however interacting with an image (Masuda, et.al, 1991), as well as the embedding of geologic knowledge into small autonomous programming routines (Rasco, 1999).

1.1 Motivation and aim

For the discrimination of geologic (e.g. possible faults), topographic (ridges, drainage segments) and non-geologic lineaments (e.g. manmade lineaments and agricultural boundaries) and their automated identification, geologic and geomorphological information is required. However, 2-D and 3-D geologic information is not exclusively acquired from a

single type of geo-data, but multi-scale and multi-type geodata are required.

So far, the research efforts towards lineament identification were restricted to the application of low-level vision algorithms (early edge detection operators) for the automated lineament extraction (Morris, 1991), the design of an expert system for lineament identification, without producing final image results (this was rather a descriptive process) (Masuda, et.al, 1991), as well as the embedding of geologic knowledge into small autonomous programming routines (Rasco, 1999). These routines produced single geologic lineament maps, thus geologic knowledge has not integrated with other land cover classes in the same image and therefore, the simultaneous processing of multiple data sets was unavailable.

Taking these limitations into consideration, a knowledge-based approach was developed for the automatic identification and classification of the topographic and geologic lineaments. It incorporated low-level to high-level vision techniques, including three main stages: (1) Remote Sensing and edge extraction procedures, (2) Data integration and segmentation, and (3) Object-oriented knowledge base design and fuzzy classification.

2. METHODOLOGY

2.1 Study area and data used

This work was conducted on a selected region of Alevrada District, Central Greece. The region of Alevrada is characterized of sedimentary terrain with many faults with horizontal displacement, joints, as well as syncline and anticline folds. The study area belongs to the Gavrovo geotectonic zone and consists of Cretaceous and Upper Paleocene – Eocene successions of limestone, Upper Eocene – Oligocene flysch, and Quaternary alluvia (I.G.M.E., 1989). From the observation of the structural map and the corresponding satellite image it was derived that the majority of the faults in the study area of Alevrada lie in the boundaries of that lithologic layers, as it is presented in Figure 1 and the dominant structural directions are the NW-SE and the NE-SW.

The input dataset of the LIS contained the following (initial and created) data:

1. The Landsat 7 - ETM+ satellite image of the Alevrada District, acquired on August, 6, 1999.
2. An edge map derived by the *EDISON* edge extraction algorithm, containing the edges to be classified.
3. The structural and the lithologic layers derived from the pre-processing phase and containing the information of the actual position of the dominant geologic lineaments of the scene (faults) and the lithologic unit boundaries. Lineaments to be identified as faults appeared on the borders of the lithologic units created by successive sedimentation.

From the comparison of all ETM+ bands, it was observed that the ETM-4 and the ETM-5 bands provided the best visualization of the lineaments. In Figure 1(b), band 5 of a subset of a Landsat-7 ETM+ image with a size of 338x518 pixels is presented. A small sub-region of the study area was

selected to show the results of the algorithm implementations, because these results are more evident and distinct in smaller parts than in the whole scene.

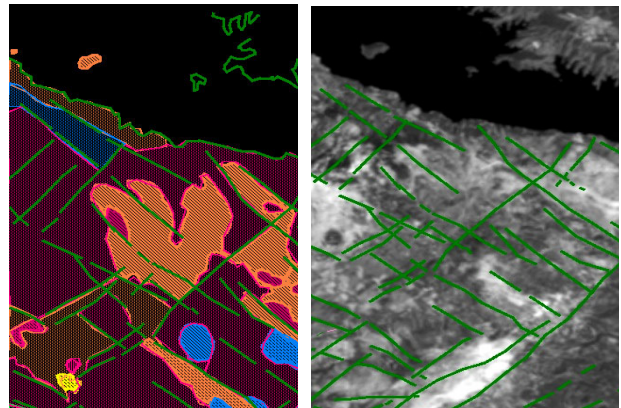


Figure 1: (a) The structural and the lithologic information layer digitized on the geologic map (Courtesy of I.G.M.E., 1989) (left), and (b) Digitized structural map features (faults and joints) as an overlay on the ETM-5 band – District of Alevrada – Pixel size 338x518 (right) (adopted from Mavrantza and Argialas, 2002).

2.2 Image pre-processing

In the pre-processing stage, the satellite image of the study area was georeferenced into the Transverse Mercator Projection and the Hellenic Geodetic Datum (HGRS87).

The geologic map of the study area of Alevrada with scale 1:50.000 was scanned. The structural (faults, fractures, joints and folds) and the lithologic information layers were created by on-screen digitizing of the geologic map.

The next step was the geometric registration of the Landsat-7 ETM+ satellite image with the digital geologic map. This image was then radiometrically corrected by subtracting the path radiance from the visible bands. These geologic layers were constructed in order to be introduced into the designed knowledge-based lineament identification scheme (LIS).

2.3 Image processing: Remote Sensing / Edge extraction methods and techniques

Digital Remote Sensing and edge extraction techniques were applied in order to create proper thematic and edge maps which were used as input data to the lineament identification scheme.

For the study area of Alevrada, the semantic framework for the construction of the knowledge-based lineament identification scheme was based on the satellite image and the geologic map. The satellite image was processed in order to provide adequate spectral information related to vegetation, lithologic sub-classes of successive sedimentation in areas containing lineaments. In turn, the geologic map provided (a) the exact location of ground-verified faults and (b) the presentation of extended lithologic units of diverse geologic eras. The aforementioned information was represented in terms of rules, classes and attributes during the design of an object-oriented lineament identification scheme. The knowledge-based scheme of Alevrada only identifies geologic faults and not topographic lineaments due to the lack of 3D since a DEM was not available.

The scope of the investigation of applying Remote Sensing and edge extraction methods and techniques is the identification on the edge map of the following features.

- *Vegetation covering lithologic sub-classes.* For the visual (qualitative) identification of the vegetation that covers the surficial lithologic entities (and their distinction from barren soil), as well as the vegetation covering tectonic features, the pseudocolor composites RGB-432 και RGB-543 were created from the satellite image (Sabins, 1997). These composites were introduced into the knowledge-based scheme for constructing rules for extracting the inherent classes of interest using Fuzzy Membership Functions (FMFs) related to spectral mean values of classes in the selected spectral bands. In addition, the application of the vegetation index NDVI was considered as a quantitative measure of vegetation content and vigor. The NDVI output was used as input data for the construction of rules using FMFs for the accentuation of land cover classes of different vegetation content and vigor, as well as for the discrimination among vegetation, bare sediments and very bright areas (roads). Vegetation is an indicator of certain lithologic sub-classes, and is interrelated with water penetration and susceptibility to erosion. For example, sedimentary areas covered by sandstone and shale might be covered by forest species and intense cultivation, but on the other hand, in humid areas, limestone (particularly, dolomitic limestone) is less *penetrated by water and* therefore, not covered with vegetation (Lillesand and Kiefer, 2000).

- *Lithologic sub-classes forming extended lithologic units contained on the geologic map.* The localization of the inherent lithologic sub-classes was performed by creating RGB composites of the Principal Components derived from the PCA method. In this composite, spectral sub-classes were discriminated, which correspond to extended lithologic units (Figure 2). ISODATA classification led to the derivation of the inherent spectral sub-classes, which were recognized by combining photointerpretation of the PCA output and were then introduced into the knowledge-based lineament identification scheme (Figure 3). In particular the application of PCA and ISODATA enabled the spectral discrimination of additional sub-classes of quaternary shale and cretaceous limestones indicated with thick arrows in Figures 2 and 3.

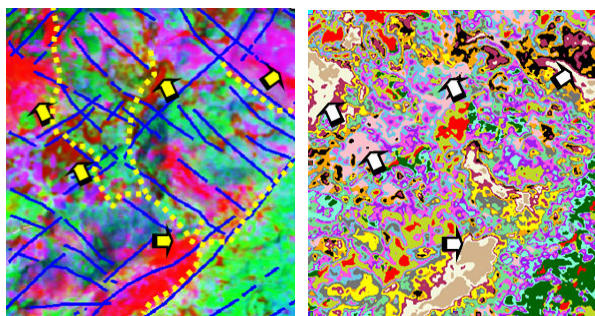


Figure 2: PCA_RGB 132

Figure 3: Thematic color composite for the lithologic map of the same area derived using the ISODATA unsupervised classification with 16 spectral classes. It should be noted that there is a correspondence between identified spectral classes and those spectral regions of Figure 2, presented with thick arrows.

Moreover, edge extraction of the output map was also performed. Various optimal edge detectors from the domain of Computer Vision, such as the algorithms by Canny and the *EDISON* algorithm were applied on the satellite image, in order to derive the most suitable edge map. This edge map served as input to the developed LIS, as being the edge map for the classification of specific lineament types. The edges cover *all* possible linear features, including also non-significant lineaments (e.g. road segments, etc).

The evaluation of the applied optimal edge detectors was conducted using qualitative (visual consistency) and quantitative criteria (use of the *Pratt* (Abdou and Pratt, 1979) and the *Rosenfeld* (Kitchen and Rosenfeld, 1981) evaluation metrics) in combination.

2.4 Data introduction and Multi-scale Hierarchical Segmentation

The method employed for the extraction of primitive objects to be classified during the object-oriented fuzzy classification process, was the innovative method proposed by Baatz and Schäpe (2000).

The conceptualization behind the design of the final structure of the participating hierarchical levels for the study area of Alevrada was based on data availability. The geologic map was decomposed into two different information layers, which in turn were used as two separate segmentation levels of tectonics (**faults**), and lithology (classes containing extended **lithologic units** of different geologic periods) The ETM+ image was used for the identification of the diverse inherent spectral land cover classes (**geologic sub-classes** and **vegetation**). The information of lithologic units was derived from the **lithology layer** of the geologic map (magenta explanatory box in Figure 4). The information related to the **lithologic sub-classes** was derived from the LANDSAT-ETM+ image (green explanatory box in Figure 4), while the edge map containing edges to be identified as geologic lineaments, was derived from the application of the *EDISON* algorithm (blue explanatory box in Figure 4). **The In region lineaments** are lineaments that lie in the **lithologic sub-classes** and were detected by using the *EDISON* edge map and the ETM+ image in the same segmentation layer. On the other hand, the **Border lineaments** are those lineaments that lie on the borders of the **lithologic units**. The border lineaments were detected by using the *EDISON* edge map and the lithology layer in the same segmentation layer. The border lineaments in this study area were verified as **Faults** using the information derived from the tectonic map (red explanatory box in Figure 4).

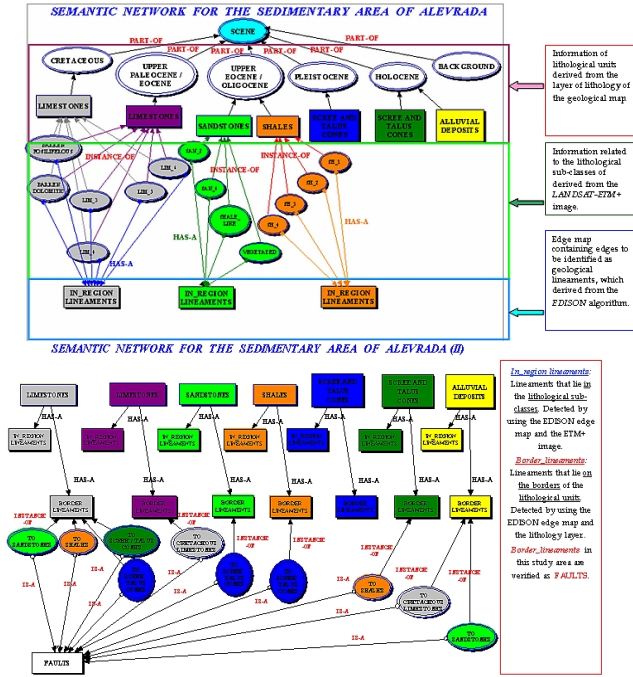


Figure 4: The semantic network for the representation of knowledge for the study area of Alevrada.

For the design of the object-oriented LIS of the study area of Alevrada, six (6) hierarchical segmentation levels were created in a certain order, data membership values (0.0-1.0) per level, and segmentation parameters were defined and were presented in Table 1.

Due to the diversity of the data format (raster – vector), the proposed level organization for performing segmentation was the result of a trial-and-error process (horizontal and vertical parameter combinations). The parameter selection was made so that every object should be segmented in a way that would allow the extraction of primitive object boundary information as well as its information content.

MULTI-SCALE SEGMENTATION PARAMETERS

DATA TYPE	Scale Parameter (LEVEL ORDER)	Color	Shape	Shape Criterion	
				Smoothness	Compactness
EDISON map	6 - (6)	0.7	0.3	0.7	0.3
Lithologic unit level	6 - (5)	0.7	0.3	0.7	0.3
ETM+ / EDISON	6 - (4)	0.7	0.3	0.7	0.3
ETM+ / EDISON	6 - (3)	0.7	0.3	0.7	0.3
Tectonic level	6 - (2)	0.7	0.3	0.7	0.3
Tectonic level	6 - (1)	0.7	0.3	0.7	0.3

Table 1: Data entry into the LIS of Alevrada – Data types and multi-scale segmentation parameters.

2.5 Object-oriented knowledge base design and classification

After the stage of segmentation of digital geodata layers into object primitives, follows the stage of the creation of the object-oriented knowledge base and the classification of the segmented objects into meaningful semantic classes that represent the natural scene. During the design of the knowledge base the following points have been taken into consideration.

- The determination of the appropriate object classes and sub-classes in every segmentation level.

- The determination of class attributes. These attributes were based on the spectral and geometric features of each class, and on the spatial relations and context. The attributes to be inherited by the sub-classes followed the logic “from general-to-specific”. In addition, these attributes should be properly connected with the AND, OR, MEAN relations, according to the “weight” of the criterion that assigns each object to a specific class.

- The determination of the use of the Fuzzy Membership Functions (type of function and membership values), alone or in combination with the Nearest Neighbor Method.

- And finally, the determination of proper classification order of each segmentation level. The classification order was not determined by the segmentation level order, but from the determination of the FMFs and the bi-directional (top-down and bottom-up) linking of attributes at different hierarchy levels in order to assign objects to each class.

The classification was conducted using six (6) classification levels in the followed order.

- LEVEL 6:** At the hierarchy Level 6, the objects were assigned into 2 classes, namely the class **ED-lineaments** and the class **ED-non-lineaments**. The distinction of those classes was based on the creation of the *FMF* of the color mean value of the participating edge map.
- LEVEL 2:** At the hierarchy Level 2, the objects were assigned into 3 classes, namely the class **Structural Map_non-Faults**, the class **Structural Map_Faults** and the class **Structural Map_Joints**. The distinction among those classes was based on the creation of the *FMFs* of the color mean values for R, G, B of the participating map and their logical AND linking.
- LEVEL 3:** At the hierarchy Level 3, the objects were assigned into 8 classes concerning the classes of the lithologic units from Paleocene to Quaternary (which are interrelated with fault localization), namely the classes: Shales - Upper Eocene-Oligocene (**Flysch of Aitoloakarnania Syncline (L3)**), Scree and Talus cones – **Pleistocene (L3)**, Scree and Talus cones – **Holocene (L3)**, Sandstones - Upper Eocene-Oligocene (**Flysch of Aitoloakarnania Syncline) (L3)**, Limestones - Upper Paleocene-Oligocene (**Gavrovo Zone) (L3)**, Limestones - Cretaceous (**Gavrovo Zone) (L3)**, Background (**L3)** and Alluvial deposits – Holocene (**Quaternary) (L3)**. The distinction among those classes was based on the creation of the *FMFs* of the color mean values for R, G, B of the participating lithology map and their logical AND linking.

4. **LEVEL 4:** At the hierarchy Level 4, the classification into *lithologic sub-classes* at the boundaries of the extended lithologic units was performed. Lithologic sub-classes were identified with the assistance of ISODATA output and classified on the ETM+ image representing the extended lithologic formations of Level 3. In particular, Level 4 contains the following classes: (1) **Shale:** This class contains 4 sub-classes: **shale_1**, **shale_2**, **shale_3**, and **shale_4**. (2) **Scree and talus cones:** This class contains 3 sub-classes: **Scree and talus cones_1**, **Scree and talus cones_2** and **Scree and talus cones_3**. (3) **Sandstone:** This class contains 4 sub-classes: **Sandstone_shale-like**, **Sandstone_2**, **Vegetated Sandstone** and **Sandstone_4**. (4) **Limestones:** This class contains 6 sub-classes: **fossiliferous limestone (barren)**, **dolomitic limestone (barren)**, **limestone_3**, **limestone_4**, **limestone_5** and **limestone_6**. (5) **Background** and (6) **Alluvial deposits**. The distinction among those classes was based on the creation of the *FMFs* and the use of NNM with color value criteria and relations of existence in different inheritance levels.

5. **LEVEL 5:** At the hierarchy Level 5, the interrelation among the edges of the edge map and their position (at the borders of lithologic units or inside the lithologic sub-classes) was examined. For the creation of Level 5, the image of Level 4 had to be classified into further nominal classes inside the lithologic subclass / unit and at the border of the lithologic units (e.g. **in f.sh lineaments (L5)** and **border of f.sh lineaments (L5)** (where **f.sh** for flysch)). The distinction among those classes / sub-classes was based on the creation of the *FMFs* using spatial relations (neighborhood, distance) and existence relations to other (upper or lower) levels of hierarchy.

6. **LEVEL 1:** At the hierarchy Level 1 the final assignment of the edges on the edge map into **faults (faults and Structural faults (verified))** and **non-faults**, was performed, based on the information of the tectonic layer, which was used for verification due to lack of additional information (ground-truth data and DEM information). The distinction among those classes / sub-classes was based on the creation of the *FMFs* using spatial relations (neighborhood, distance) and existence relations to other (upper or lower) levels of hierarchy using AND / OR logical relations.

2.6 Results and Discussion

In this section, specific products of the knowledge-based scheme are presented, from all stages of processing (Figures 5-8).

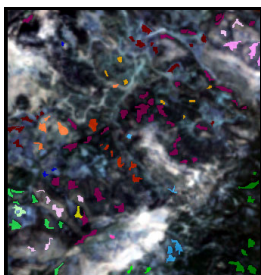


Figure 5: The training sample level as input to the Standard Nearest Neighbor classification method, in order to classify the inherent lithologic sub-classes on the ETM+ image – Level 4.

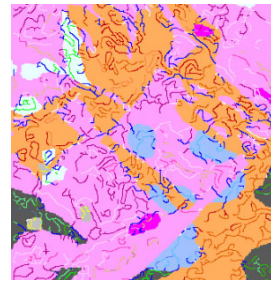


Figure 7: The Level 5 classification output and the corresponding class hierarchy. Note that lineaments that lie at the borders of lithologic units are depicted with blue color, while lineaments inside the geologic sub-classes / units are presented with other colours.

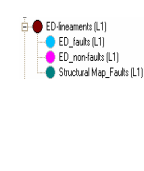
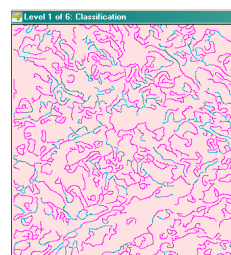


Figure 8: The Level 1 classification output and the corresponding class hierarchy – Final lineament map, where lineaments correspond to faults

In Figure 10 the classification stability map is presented. It should be noted that red edges on the stability map, which indicate points of **minimum stability** correspond to **joint edges** on the tectonic map and the edge map, and lie on the major tectonic directions of the study area of Alevrada, as appear in Figure 9.

Finally, for the study area of Alevrada, and from the comparison of Figures 9 and 10, it was visually inferred that there was a high degree of coincidence of the results of the knowledge-based scheme and the tectonic map of the area. In all expected (according to the tectonic map) directions, edge pixels have been correctly identified and the classification stability map serves as an additional, qualitative indicator of adequacy of the classification.

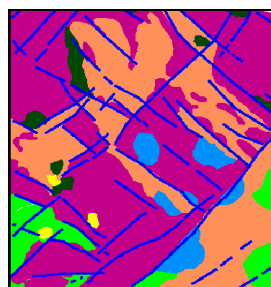


Figure 9: Overlay of the tectonic layer (blue lines) on the lithology layer (colored background) .

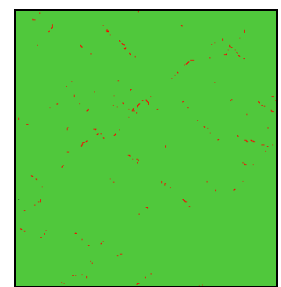


Figure 10: Classification stability map for Level 1.

3. CONCLUSIONS

A knowledge-based scheme was developed for the identification and classification of the edges into geologic

lineaments. This methodological framework aimed to the automatic identification and classification of the topographic and geologic lineaments. The output result of the system was a classified lineament map containing the geologic lineaments of the study area (faults) and the lineaments, which were not identified as faults (non-interest lineaments).

The developed knowledge-based methodological framework, which combines multiple geodata types and techniques in the joint domain of Remote Sensing, Computer Vision and Knowledge-based systems enabled the derivation of final thematic maps of topographic / geologic features, by taking into consideration the study area, the spectral behaviour of the satellite geo-data, as well as the production accuracy of the input data, which were created with automated procedures. Nevertheless, the proposed framework is strongly task-dependent and cannot be “generalized” to cover all geologic cases, but instead, it is open to be adopted to each case study with adjustments in the knowledge base design.

4. REFERENCES

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