Textural Analysis and Structure-Tracking for geological mapping: Applications to sonar images from Endeavour Segment, Juan de Fuca Ridge

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Abstract - The volume of data collected by side-scan sonar during seafloor surveys has become larger and larger as the resolution of these systems has improved. As a result, new image processing techniques need to be developed to partly automate the interpretation of this increasing wealth of data. The first two steps in the geological analysis of a new image usually are the mapping of linear structures, and of morphologic units. These maps are then used in tectonic and geological interpretations. Linear features are here detected by Adaptive Filtering. Their properties (length, direction, sinuosity, ...) are computed and quantified by the new Structure-Tracking algorithm. Mapping of morphologic units is addressed by a textural analysis method, based on Gréy-Level Cooccurrence Matrices. We have applied these techniques to high-resolution sonar images of the Endeavour Segment, Juan de Fuca Ridge. Separation of geologically meaningful regions can be easily attained using our textural analysis method. Some regions can be distinguished by numerical methods, whereas visual interpretation had to rely on supplementary data (photos, dives).

I. INTRODUCTION

Data acquired in remote sensing studies are becoming more and more important in terms of volume, as the resolution of the sensors used in these studies has been steadily increasing. This is particularly noticeable in marine sciences, in which side-scan sonars are a major tool to image the seafloor and interpret its characteristics. The wealth of data collected by side-scan sonars furthers the need to develop new relevant image processing techniques.

II. STRUCTURE - TRACKING

A. Adaptive Filtering

One of the very first tasks involved in the geologic interpretation of new sonar images is to map linear features. In the case of mid-ocean ridges, they usually consist of faults and fissures. Knowledge of their distribution is crucial to the understanding of the tectonic setting of a spreading center, whereas the orientation of faults is indicative of the stress field in a given area.

In the case of sonar images, the method which proved the most adequate to detect linear features is gradient filtering.

Linear structures, such as faults and fissures, are characterized by rapid changes in luminosity, and hence a high gradient. For a 3x3-pixel masking, 8 directions are available, and therefore 8 filtered images should be compared, at each time, to the original one to resolve linear structures. The Adaptive Filtering algorithm [1] avoids this by computing the gradient in all directions at the same time. Only the directions of gradients, whose amplitudes are superior to a pre-selected threshold, are recorded in the output image. This threshold, and the type of filters (Sobel, Kirsch ...) are chosen by the user, at the beginning of the process, and may be changed interactively during processing.

B. Structure-Tracking

Once linear features are detected, their properties can be quantified by following these features along their strike. Several methods may be used. Heuristic methods assume there exists an a priori knowledge about the structures. This is obviously not the case for geologic features, for which little can be assessed before interpretation. "Blind" methods link neighboring pixels without using any prior information, but may lose some details or mix distinct features. Structure-Tracking [1], however, fully uses information provided in the previous step by the gradients, and is better adapted to geological applications. The image is swept from top to bottom, and left to right. Each time a point is found, where the amplitude of the gradient is superior to the threshold, it is considered to be the beginning of a new feature. The algorithm looks for neighboring pixels with the same properties, according to a specific searching pattern. In case of ambiguities, choices are made according to local and global properties of the current feature. End of a feature is reached when there are no neighboring pixels left.

C. Output parameters

Several parameters are recorded during the Structure-Tracking algorithm. The real length of each feature is computed according to a selected projection (Mercator, sinusoidal, ...). The mean direction, its standard deviation, and a histogram of the changes of directions along each structure, are also available. Histograms may show, for example, different trends in en-chevron structures [1]. Another important parameter computed is the sinuosity of the structure. All these values can be used in histograms, or rose diagrams, for

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tectonic interpretations. Their analysis may lead to mapping of only features with specific lengths, or specific sinuosities, which would be difficult to achieve manually.

III. TEXTURAL ANALYSIS

A. Grey-Level Cooccurrence Matrices

In a sonar image, distinct regions are visually identified by geologists on the basis of their appearance, or texture, before being interpreted in a geological framework. Visual analysis is obviously qualitative and subjective. Indeed, for physiological reasons, the human eye cannot distinguish moments of order greater than 2. This inherent limitation of human interpretation can be overridden by numerical methods, which offer a quantitative and more objective alternative.

Spatial distribution of grey levels in an image, i.e. texture, can be accurately described by the average relationships that grey-levels have with one another [2]. Texture is quantified by sets of matrices $\{P_D(i,j)\}$, called Grey-Level Cooccurrence Matrices (GLCM). Each entry $P_D(i,j)$ is the relative frequency of apparition of two points, with respective grey-levels i and j , located at distance $D(d,\theta)$ apart (d : distance and θ : angle between pixels). If the image is quantized with NG grey-levels, the GLCMs will be $NG \times NG$ arrays. They are computed on small windows across the image, with a size SZ . These parameters must be carefully chosen, and depend on sensor's capacities and scales of objects to analyze. Once computed, GLCM are characterized by statistical measures, called textural indices [2]. For example, entropy quantifies the disorder of the texture, i.e. roughness, and local homogeneity quantifies the small-scale smoothness. Directional dependence of the local textures may also be quantified.

B. Mapping of Characteristic Geologic Units

Supervised classification of individual textures and morphologic units is preferred to unsupervised one, at least for a first step. Small regions, typical of the geological features encountered in the image, are chosen by geologists as representative of morphologic units of interest. Grey-Level Cooccurrence Matrices and textural indices are then computed in these different "training zones". Parameters (number of grey levels, computation window size, and interpixel displacement) are adjusted, to obtain the best separation between the training zones. Orientation θ in the displacement $D(d,\theta)$ is very sensitive to the sensor's attitude (roll, pitch, and yaw). Identical structures will not have the same GLCM unless the influence of directions is averaged. As recommended by [3], GLCM are computed for θ values of 0° , 45° , 90° , and 135° , before averaging. This reduces displacement D to distance d .

As variations in brightness can occur from one image to the other, or in the same image, we changed the numerical expression of some indices by adding normalization factors,

as in [4]. Only the textural indices allowing a good separation are retained. This can be done either visually, if the number of training zones is small, or numerically (Karhunen-Loeve analysis). Validity of these results is assessed by extension to similar zones located elsewhere in the image. For example, several lava regions are compared to check whether they possess similar textural indices. The next step is labeling and definition of Look-Up Tables in the parameter space. Computation of the few retained textural indices leads to segmentation of the original image thus giving the final product, a map of specific geological regions.

IV. GEOLOGICAL APPLICATIONS

A. Geological Setting of the Endeavour Segment

Located in the NE Pacific Ocean, the Juan de Fuca Ridge marks the boundary between the Pacific and Juan de Fuca plates (Fig. 1). Our study focused on the Endeavour Segment, a well characterized portion of the ridge [5]. The central part of this 90 km-long segment has a minimum depth of 2050 m. The axial valley is well-defined, and marked by a narrow zone of faults and fissures. Intense hydrothermal activity is concentrated within the axial valley, with large fields actively venting fluids, with temperatures in excess of 380°C .

A multisensor survey (CREST-1991) was recently conducted along the Endeavour Segment. The DSL-120 kHz sonar survey covered the entire segment, and a combination of instruments (200-kHz sonar, 675-kHz Mesotech profiler, and video and electronic still camera systems for specific areas), were used to image the area around the Main Endeavour Field (MEF), at $129^\circ06'\text{W}$ and $47^\circ57'\text{N}$. Acoustic and optical seafloor imagery, and bathymetry, were produced at resolutions varying from tens of meters to centimeters and scales from kilometers to decimeters [6] [7].

The DSL-120 kHz image used in the present study (Fig. 2) is centered on the Main Endeavour Field and has a pixel resolution of one meter. The track of the side-scan sonar towfish is oriented 010°N . Most of the features observed along the axial valley are present in this image; talus, lava flows, sediment covers, hydrothermal deposits ... Furthermore, previous studies [8] [9] provide ground-truth data, from numerous dives and samplings.

B. Cartography of linear structures

Structure-Tracking has been used on this image with Kirsch-type filters, and a 72% threshold (Fig. 3). The processing technique highlights the fissured axial valley floor, and the main trend (020°N) of the tectonic features. It also demonstrates that the non-faulted or non-fissured areas along the axial valley of the Endeavour segment are covered by talus (white patches on Fig. 2). Cumulative lengths have been plot-

Fig. 1 : (left) plate boundaries in the NE Pacific Ocean (from [8]); (right) location of the Endeavour Segment along the Juan de Fuca Ridge. Shaded areas correspond to major seamounts in the vicinity of the ridge (from [8])

Fig. 2 : DSL-120 kHz backscatter image used in this study. Size is 512x1024 meters, pixel resolution is 1 meter. Deep-towed sonar track is vertical, in the middle of the image. Outlined are the training regions where textures were computed.

Fig. 3 : Structure-Tracking of all linear features in Fig. 2.

Fig. 4 : (left) rose diagram of cumulated lengths for all linear structures in the filtered image ; (right) rose diagram of cumulated lengths for the straightest structures (sinuosities of 1. to 1.4). The main trend of tectonic features is enhanced.

Fig. 5 : Diagram showing entropy vs. local homogeneity for the first 7 training zones. Region 1 (talus and pillow basalts), is located in the diagram between regions 2 (lava) and 3 (faults). This can be explained by the heterogeneous nature of Region 1, mixing textures associated with pillow basalts and textures associated with fissures in the talus.

Region 1: talus, pillow basalts	stars
Region 2 : lava flows	circles
Region 3 : faults	crosses
Region 4 : hydrothermal vent	stars
Region 5 : hydrothermal vent	crosses
Region 6 : lava type	circles
Region 7 : shadows	stars

ted for very straight features (curvature/length ratio of 1 to 1.4) (Fig. 4). Their repartition enhances the fact that 020°N-trending features are very straight, whereas other trends exhibit higher sinuosities. Remarkable consistency of fault orientation parallel to the ridge trend supports, and gives quantitative constraints, to the models of extensional tectonics dominating the evolution of the Endeavour Segment [5] [8]. The capability to map features by intervals of lengths, directions, or sinuosities, will greatly enhance previous small-scale tectonic interpretations in this area.

C. First applications of textural mapping

We selected a set of 7 training zones to encompass the different geological features visible in this image; talus, lava flows, faults, hydrothermal vents, and shadows. The size of training zones is 32x32-pixels, wholly covering geological objects of interest. The optimal parameters were empirically defined as the ones leading to the best separations between Training Zones. This image could be quantified on 32 gray-levels, and the GLCM computed in 20x20 windows, with an interpixel displacement of 15 pixels. These values are in agreement with the scale of geological objects. In each region, 144 points are therefore computed. From the 20-plus textural indices available, the two most useful ones are entropy (associated to roughness), and local homogeneity (a measure of smoothness) (Fig. 5). Usefulness of these two indices is further assessed, by computing them on the 22 regions outlined in Fig. 2. Accuracy of the classification depends on the complexity of the region. Shadows are recognized with a success rate of 100%. Talus and lava flows are recognized with accuracies ranging from 60 to 85%. Another, rougher, type of lava flow is distinguishable with accuracies of up to 100%. Hydrothermal vents are recognized with high accuracies (>75%), and may even be separated by types. These overall results are therefore very good, although some additional tests still need to be made. It may be worth noting that these different regions could not be separated with first-order descriptors (contrast, ...) at all.

IV. CONCLUSION

In order to partly automate the interpretation of side-scan sonar data, we applied two new image processing methods. The first one, Structure-Tracking, follows all linear features, and gives useful quantitative informations (lengths, directions, sinuosities ...), as well as maps and rose diagrams. The second one, Textural Analysis, distinguishes morphological units on the base of their textures. These two methods are applied to sonar images of the Main Endeavour Field, where they demonstrate their capabilities.

The next steps, currently under way, concern labeling of the parameter space, and segmentation of the sonar image into its morphological units. The output map will be further

compared with results of manual analysis. Geology of similar regions with distinct textural signatures is also being investigated. Application to other images of the same zone will assess the importance of other parameters, such as angle of insonification, or spatial resolution. Our final goal is to produce a set of maps and quantitative data to enhance and speed up the geologic interpretation of this region, as well as other parts of the segment.

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