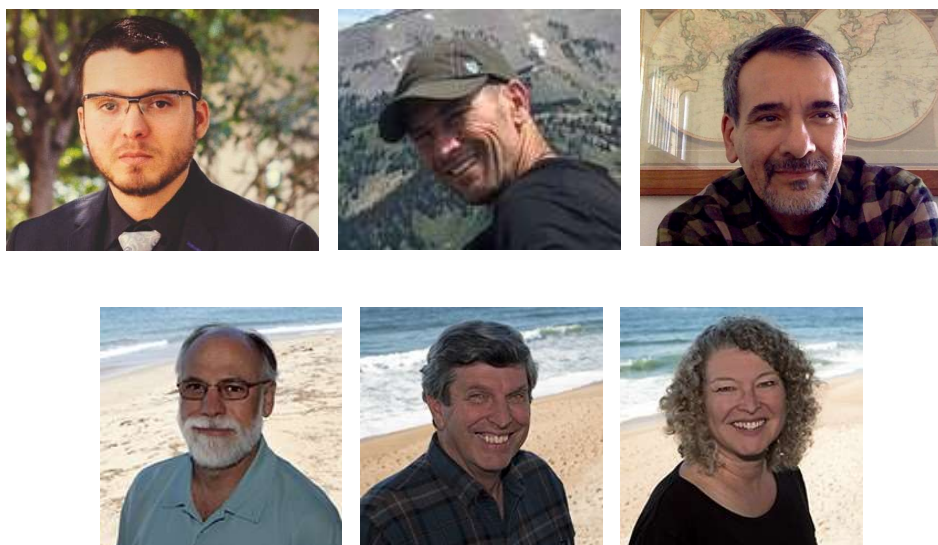


A new Method for Fault-Scarp Detection Using Linear Discriminant Analysis (LDA) in High-Resolution Bathymetry Data from the Alarcón Rise and Pescadero Basin, Gulf of California.

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PRESENTED AT:



Abstract.

The mapping of faults and fractures is a problem of high relevance in Earth Sciences. However, their identification in digital elevation models is a time-consuming task given the fractal nature of the resulting networks. The effort is especially challenging in submarine environments, given their inaccessibility and difficulty of collecting direct observations. Here, we propose a semi-automated method for detecting faults in high-resolution bathymetry data (~1 m horizontal and ~0.2 m vertical) of the Pescadero Basin in the southern Gulf of California, which were collected by MBARI's *D. Allan B* autonomous underwater vehicle. This problem is well suited to be explored by machine learning and deep-learning methods. The method learns from a model trained to recognize fault-line scarps based on key morphological attributes in the neighboring Alarcón Rise. We use the product of the mass diffusion coefficient with time, scarp height, and RMSD error as training attributes. The method consists in projecting the attributes from a three-dimensional space to a one-dimensional space in which normal probability density functions are generated to classify faults. The results of the LDA implementation in various cross-sectional profiles along the Pescadero Basin show the proposed method can detect fault-line scarps of different sizes and stages of degradation. Moreover, the method is robust to moderate amounts of noise (i.e., random topography and data collection artifacts) and correctly handles different fault dip angles. Experiments show that both isolated and linkage fault configurations are detected and tracked reliably.

1.- Introduction.

Seafloor maps are becoming increasingly accurate as technological advances allow the construction of ever-higher spatial resolution instruments, storage capacity, and autonomy. The new developments include autonomous underwater vehicles (AUVs) that, by navigating close to the seabed, have improved the resolution of submarine surveys several folds with respect to traditional seafloor mapping tools.

One of the major limitations concerning mapping overextended bathymetry data is the number of structures that must be processed or identified. Traditionally this has been a tedious and time-consuming task requiring manual picking of fault-scarp traces over multiple length scales and measuring properties such as fault length and displacement. Thus, the derivation of constraints and other visual clues that facilitate the design of automated detectors in gridded data is an important problem in marine geology and geosciences in general.

Here, we present a new semi-automatic method to identify fault-scarp traces on high-resolution gridded bathymetry data. This method relies on the Linear Discriminant Analysis (LDA) and fault-scarp degradation modeling in one-dimensional (1D) topographic profiles. With this method, it is also possible to estimate morphological ages of faults and fault-length scaling relationships, which is essential to understand the deformation history of actively extending zones. Our study focuses on the Alarcón Rise and the Pescadero Basin located in the southern Gulf of California (Figure 1). Both basins were mapped in 2012 and 2015 at a resolution of 1-m, with the help of the AUV D. Allan B, operated by the Monterey Bay Aquarium Research Institute (MBARI). The deformation style makes them a natural laboratory to test new methods of automated fault-scarp detection.

2.- Geologic Settings.

The Gulf of California is an oblique-divergent boundary between the North America and Pacific tectonic plates (Figure 1a). It is a rift system characterized by an array of right-stepping en-echelon strike-slip faults opening a series of pull-apart basins and short spreading segments (Lonsdale et al., 1980; Lonsdale, 1991).

The Alarcón Rise is an active spreading center located at the mouth of the Gulf of California (Figure 1b). It is the longest (~50 km) spreading segment of the rift system and has a spreading rate of ~4.9 cm/yr (e.g., DeMets et al., 2010), which accounts for 92% of the relative motion between the North American and Pacific plates (Lizarralde et al., 2007). The southwestern end of the Alarcón Rise is bounded by the ~60-km-long Tamayo Transform Fault, which connects to the 21 N segment of the East Pacific Rise. The Pescadero Transform Fault bounds the northeastern end and connects the Alarcón Rise spreading center with the southern Pescadero pull-apart basin. It is one of a series of three asymmetric grabens, collectively named “Pescadero Basin complex,” separated by short transform faults (Mann et al. (1983), Ramirez-Zerpa, et al., in preparation).

MBARI generated in 2012 and 2015 high-resolution (~1 m horizontal and ~0.2 m vertical) bathymetry DEMs for both the Alarcón Rise and the Southern Pescadero Basin (Figures 2, 3 respectively). The surveys revealed an extensive array of normal faults and fissures, cutting lava domes, volcanic cones, pillow mounds, lava sheet flows of variable compositions, and pelagic sediment deposits (Figure 2 a,b). Figure 2 illustrates active faulting, tensile fissures development, and a rhyolitic dome formed exclusively of evolved lavas at the NE segment of the Alarcón Rise in the transition between the neovolcanic zone and adjacent axial summit trough. These structures were examined in detail by Portner et al. 2018 and Vega-Ramirez, 2018. A frequency analysis performed by the later author shows that normal faults follow a power-law distribution (Figure 2c) whereas fissures follow exponential distribution (Figure 2d), features often observed in high-strain extensional tectonic environments (Cowie & Scholz, 1992; Marrett & Allmendinger, 1992; Dawers et al., 1993; Cladouhos & Marrett, 1996; Contreras et al., 1997; Gupta & Scholz, 2000b, 2000a; Kim & Sanderson, 2005; Whipp et al., 2017). The accepted interpretation is that the population has reached a point of saturation characterized by overlapping fault segments. Thus, faults lengthen primarily by coalescence, i.e., fault-tip interaction and linkage with other faults, rather than by growth or nucleation (Spyropoulos et al., 1999; Contreras et al., 2000; Gupta & Scholz, 2000a; Peacock, 2002).

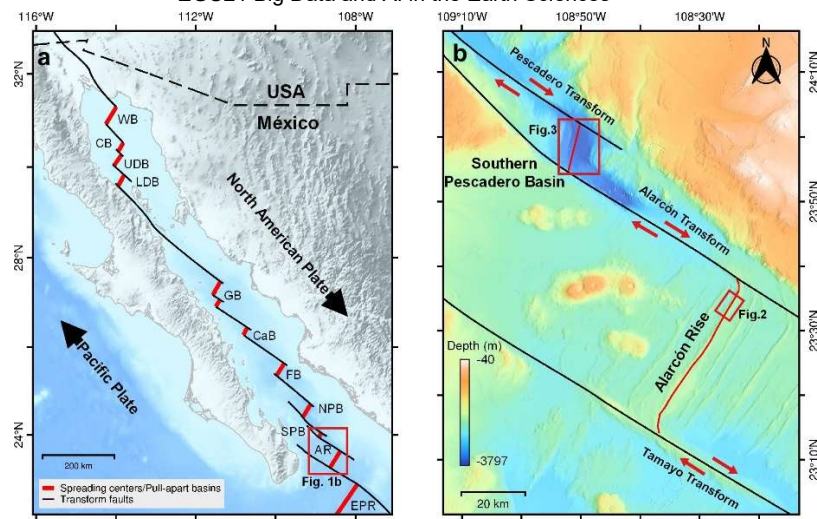


Figure 1.- a) General tectonic framework of the Gulf of California Rift System. Arrows indicate the relative motion of the North American and Pacific plates. Abbreviations: WB = Wagner Basin; CB=Consag Basin; UDB, LDB = Upper and Lower Delfin Basin; GB = Guaymas Basin; CaB = Carmen Basin; FB = Farallon Basin; SPB = Southern Pescadero Basin; AB = Alarcón Basin; EPR = East Pacific Rise. b) Bathymetry map with the regional tectonic setting of the study areas.

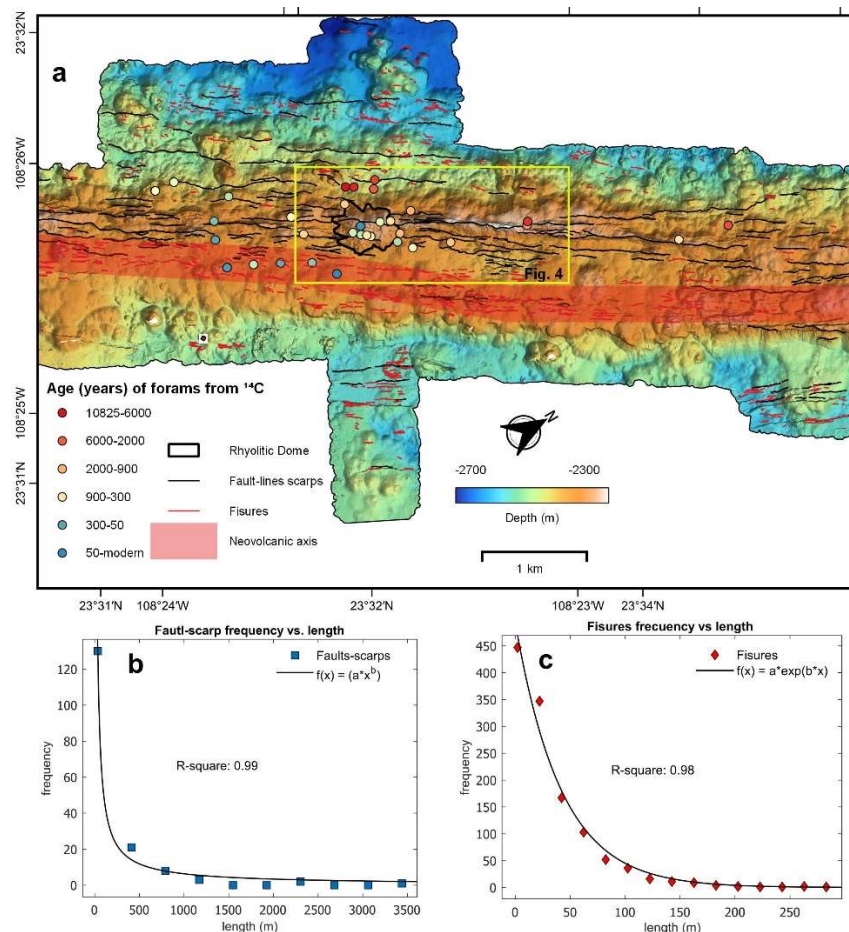


Figure 2. a) High-resolution bathymetry of the neovolcanic zone in the northern terminus of the Alarcón Rise. The ridge axis is dissected by numerous faults (black lines) and tensional fissures (red lines). Colored triangles represent the ages of foraminiferas. b) Plot of fault frequency vs. fault length. The number of faults resulting from increasing size decreases following a power law over roughly three magnitudes orders. c) Plot of fissure frequency vs. length. The black line represents the exponential theoretical model. The yellow rectangle shows the area that correspond to Fig. 5.

The Southern Pescadero Basin is a stretched sigmoidal-to-rhomboidal pull-apart basin, with a Z-shape geometry, developed between the overlapping Tamayo and Pescadero transform faults (Figure 3a). The basin is strongly asymmetric, the subsidence being controlled by a transverse system of oblique-extensional faults, linking with the limiting transforms. A discrete array of east and west-facing sub-parallel normal faults characterized the basin's central portion (Figure 3b). The faults form a nested graben structure in the N-S direction. Sediment thickness across the deep graben greatly exceeds >80 m and thin (between 20 to 50 m) over the tilted footwalls of the conjugate set of extensional faults (Paduan et al., 2018). The western walls of the nested graben are controlled by a series of left-stepping, en-echelon-arranged faults. The length (up to ~8.5 km) and vertical displacement (up to 175 m) of adjacent fault segments increase systematically westward. The curved fault geometry suggests a more complex history of soft and hard-linked segment interaction. Relay structures, such as intact and breached ramps, are also standard features observed along with the younger, innermost, fault scarp array, with the exception that individual segments are generally <5 km and exhibit straight superficial traces.

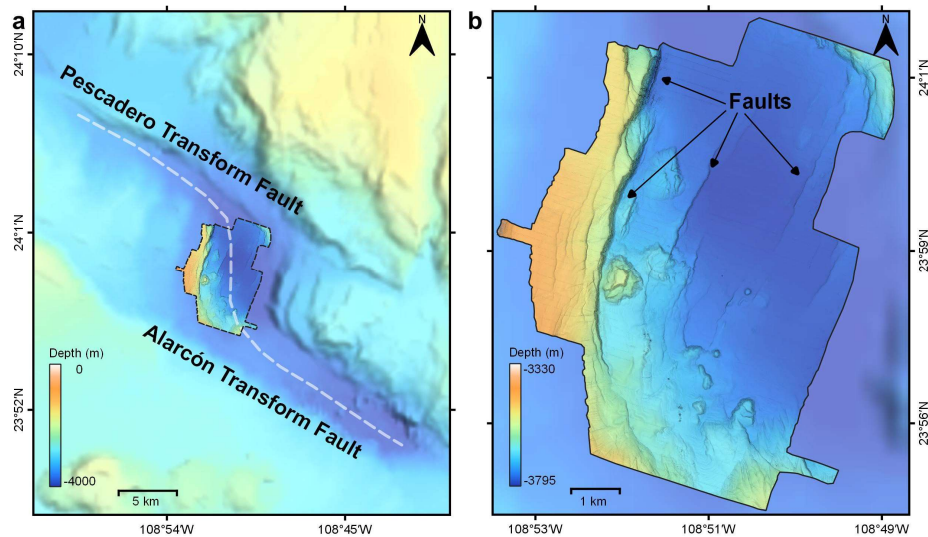


Figure 3. a) Pescadero Basin have Z-shape geometry developed between the overlapping Tamayo and Pescadero transform faults. b) High-resolution bathymetry shading map of the Pescadero Basin, arrows pointing the largest fault-scarp arrays.

3.- Fault-scarp morphology.

A fault-scarp is a tectonic landform coincident, or roughly coincident, with a fault plane that has dislocated the ground surface (Stewart & Hancock, 1990). Generally speaking, fault scarps have a step-like morphology and lateral continuity that make it easy to identify them visually in the field by aerial photographs and digital elevation models. Wallace (1977) observed that the main feature of scarps younger than a few thousand years is a steep free face, a debris slope standing about 35° , and a sharp break in slope at the crest (Figure 4).

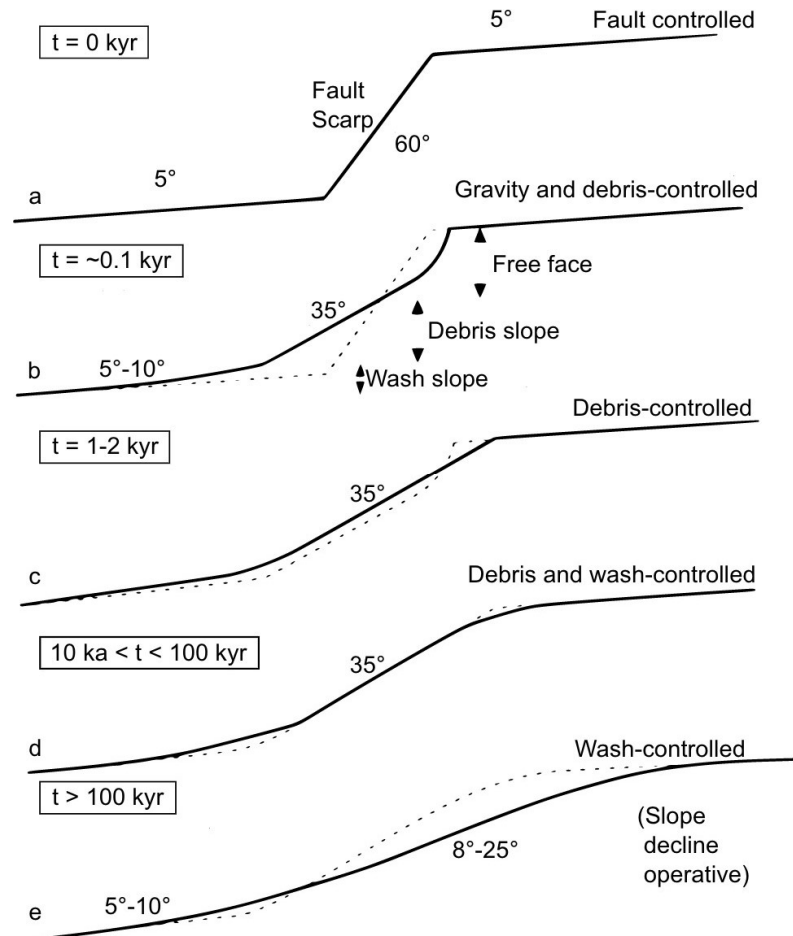


Figure 4.- Schematic representation of sequential fault-scarps degradation through time. The segmented lines represent the solid line of the previous profile. The time is in thousands of years (Modified after Wallace, 1977).

The initial scarp's fault plane generally has angles ranging between 50° and the vertical (Figure 4a). Immediately after its formation, a fault scarp begins to degrade by erosion processes. The debris created by weathering falls from the fault's free face, distributing in the scarp base (Figure 4b). The continuous transport of debris lessens the topographic slope rapidly until it reaches a value between 30° and 35° (Carson & Kirkby, 1972; Nash, 1986; Pierce & Colman, 1986). After this initial short stage that lasts around 10-100 years, scarp degradation is controlled principally by slower diffusional processes that further smooth the scarp's top and base and decrease the maximum slope beyond the repose angle reached during the initial stage (Figure 4 c-e).

Nash (1980) developed a model of fault-scarp degradation in which erosion and local sedimentation are treated as linear diffusive processes.

$$\frac{\partial u}{\partial t} = k \frac{\partial^2 u}{\partial x^2} \quad (1)$$

x is the distance measured perpendicular to the fault scarp in meters, u is the elevation in meters, t the time in years, and k the diffusion coefficient in m^2/yr . In this model, the flux of mass downslope is proportional to the local slope du/dx . Equation 1 establishes that the rate of change in elevation du/dt at a point on the scarp is proportional to the curvature at that point (e.g., Nash 1980, Colman and Watson 1980, Andrews 1985).

For the case of a right-stepping vertical fault subject to the following boundary and initial conditions $u = 0$ as $x \rightarrow \infty$, $t > 0$, $u = 2u_0$ as $x \rightarrow -\infty$, $t > 0$, $u = 2u_0$ for $x = x_f$ at $t = 0$, a solution to Equation 1 is given by the expression:

$$u(x, t) = u_0 \operatorname{erfc}\left(\frac{x - x_f}{2\sqrt{\tau}}\right) \quad (2)$$

where x_f the location of the inflection point situated in the middle of the scarp, the product $\tau = kt$ is called the "diffusion age" and has units of length squared, $\operatorname{erfc}(x)$ is the complementary error function, and u_0 is the height of the scarp (fault throw). This problem is analogous to the one-dimensional problem in a semi-infinite solid with an initial temperature distribution at $x=0$ and a surface temperature equal to zero elsewhere (Carslaw & Jaeger, 1959).

4.- Training data set.

Machine learning algorithms' objective is to extract empirical knowledge from data and then perform classification or make a prediction. There are three machine learning approaches: supervised, unsupervised, and reinforcement learning.

Here we use the supervised learning approach, which is best suited for our goal of fault-scarp classification since we already have a set of labeled data, i.e., a population of fault scarps in the Alarcón Rise. Two further advantages of this approach are that the LDA, unlike neural network algorithms, does not require massive volumes of input data, and its implementation is straightforward. Generally, it requires using a segmentation operation to isolate the objects to classify (in our case, faults), and an attribute extractor to reduce the objects to a series of values called "features." A feature is just any measurable property or characteristic that can describe the object. These features are the ultimate representation of the objects that constitute the training samples.

Before describing our training set, it is necessary to introduce first the following definitions. A "cliff" is any overhanging landform with a steep slope. A "fault-line scarp" is a cliff with a rock face produced by faulting. For a cliff to be classified as a fault-line scarp, it must satisfy the following criteria: (i) cliffs must have a length L , measured in the strike direction, $L > 4$ m, i.e., they must be clearly discernible in the 1 m resolution bathymetry, (ii) the height of a cliff must follow a relationship of the form $u_{max} = \gamma L$ where γ is approx 0.02, (iii) cliffs may display linkage structures with neighboring cliffs like bridged relay structures, which are characteristic of normal faults, and (iv) cliffs must be fresh so that erosion has not destroyed all traces of the actual plane of the fault (Figure 5). All other cliffs that are either product of differential erosion, accumulation of sedimentary deposits, and lava flows are denominated "cuestas."

The training data set consists of 163 cliffs observed in the bathymetry of the Alarcón Rise (Figure 2a). Out of these, 70 fulfilled the criteria (i)-(iv) and were classified as fault-line scarps. Fault length varies from ~35 m to ~3440 m long, and their height ranges from ~4 m to ~35 m. The talus of the faults fluctuates between 45° and 64° degrees. The fault-line scarps include 63 linked faults in one or both tips, and only seven are isolated faults. The remaining cliffs were classified as cuestas and consist mostly of low-relief hummocky flows and pillow mounds.

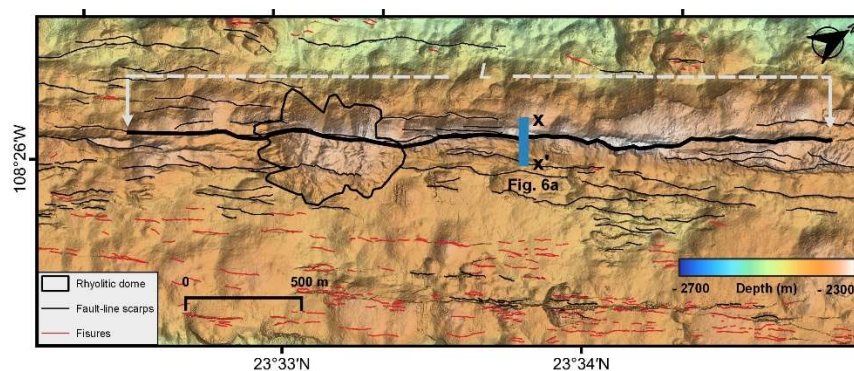


Figure 5.- a) High-resolution bathymetry of the northern section of Alarcón Rise. This is the most faulted portion characterized by a large fault-scarp cutting a rhyolitic dome. In b), two of the sharpest fault-scarps in the Alarcón Rise are highlighted by the black and gray dotted lines. The transversal red solid line represents the location where a profile is extracted to be part of the training dataset.

We extracted the diffusion age, τ , the semi-scarp height, u_0 , the inflection point, x_f , and root mean square error ϵ , from all the cliffs in our training set through a nonlinear best-fit algorithm using equation 2 (Figure 6a). In Figure 6b, we have plotted all the values obtained from the inversion in a parametric space τ^* versus u_0^* . The bluesquares are the fault-line scarp samples, and the orange circles represent the cuestas. Figure 6c, ϵ^* ranges from 0.025 to 0.095, whereas cuestas ranging from 0.01 to 0.08. Perhaps, more importantly, in both plots, the fault-line scarp samples are localized by $0.05 \leq \tau^* \leq 0.25$; meanwhile, the cuestas tend to be located at $\tau^* > 0.25$.

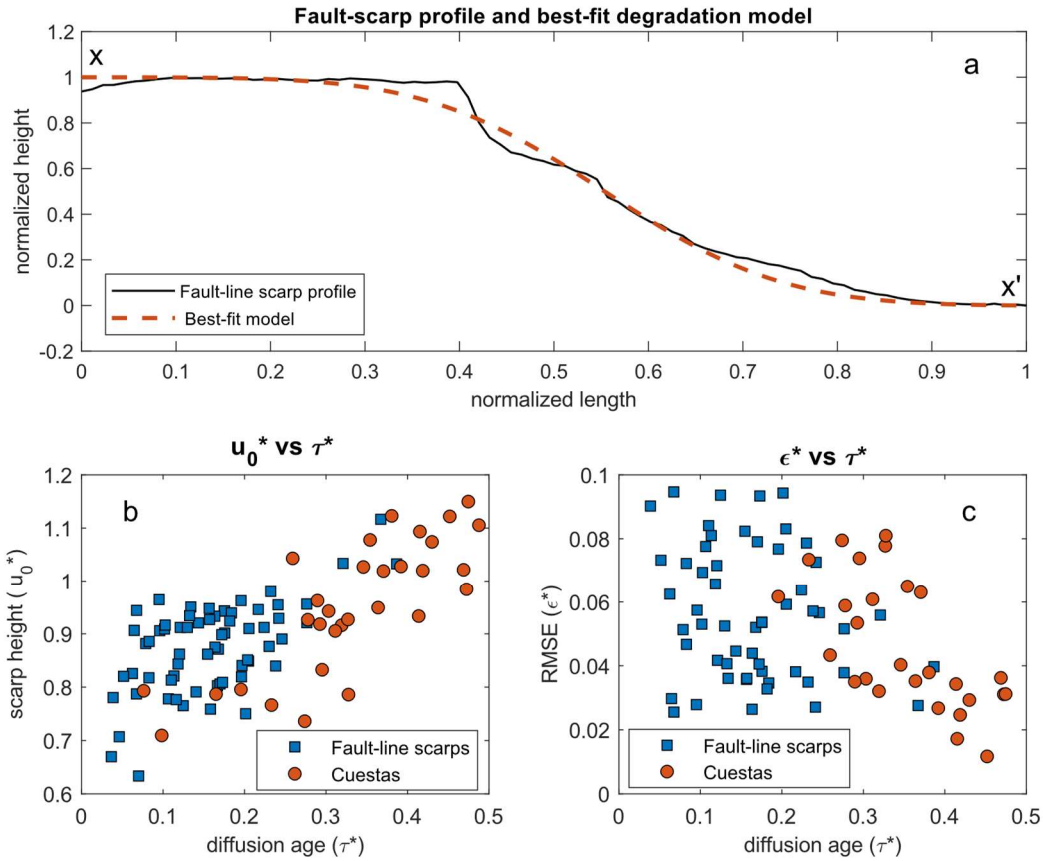


Figure 6.- a) Topographic profile across a fault-line scarp (solid line) and the best-fit model based on equation 2 b) Plot of τ^* versus u_0^* of the training features data set. Observe how fault-line scarps cluster around a value of $u_0^* \sim 1$, whereas cuestas display values of $u_0^* < 1$.

5.- LDA

In general, we expect the training set to be a confused mixture of different classes present in the data, and, naturally, we expect them to be hard to separate (Bishop 2015). LDA's main goal is to maximize the separability between the classes, making them easy to classify. To achieve this, the data are projected into a line that forms well-separated compact clusters (i.e., Figure 7).

There are three steps needed to perform the LDA technique. The first is to calculate the distance between the means (S_B) of the different classes. The second is to calculate the distance between the mean and the samples of each class (S_W). The third step is to build the lower dimensional space using Equation 3 called the Fishers criterion. Equation 3 maximizes the separability between classes (S_B) and minimizes the data dispersion (S_W) to obtain the optimal discriminant projection axis (Tharwat et al., 2017).

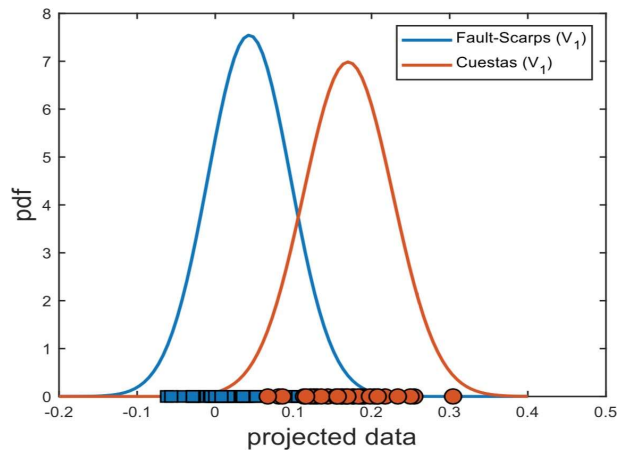


Figure 7. The plot of features projected to one-dimensional space (line) where the classes represented by the blue squares and orange circles are well-separated. Probability density functions (Gaussian) are built for each class projected.

6.- Fault-line scarp detection.

We used a window search approach to detect fault-line scarps in a total of 515 profiles of the Pescadero Basin bathymetry (Figure 3b). The profiles for fault-line scarp detection were extracted every 20 rows-vectors (20 m) until reaching the last one in the grided bathymetry data. Skipping row-vectors allows us to reduce computation time. The search windows advance every 5 m from left to right, as shown in Figure 9. The profile section matching with the window interval is fitted with the fault-line scarps degradation model (Equation 2) to get the features τ^* , μ^* , and ϵ^* . Then, these features were projected to a plane normal to the eigenvector V_1 (Figure 7). The classification (fault-scarp/cuestas) was performed according to the highest value of the pdf.

Then we test six different search window sizes: 200 m, 400 m, 600 m, 800 m, 1000 m, and 1200 m. The most consistent result is given by the search window of 400 m (Figure 10).

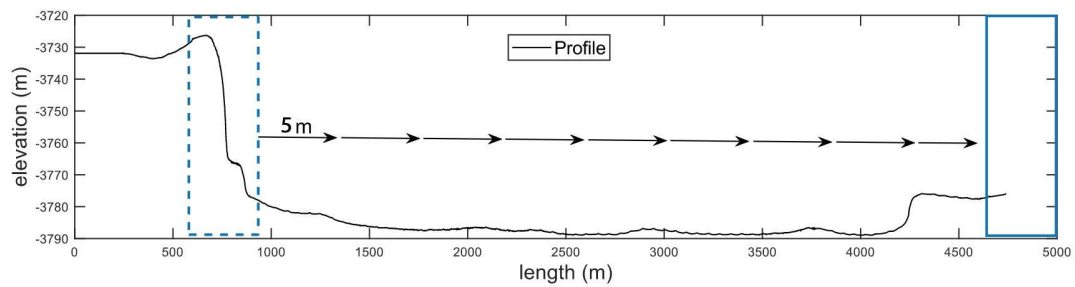


Figure 9.- Representation of the window search approach for detecting fault-scarp in bathymetry profiles. The rectangle in blue color with dotted lines represents the search window's initial position, and the rectangle with a solid line represents the final position. The arrows represent the advancing direction of the searching window.

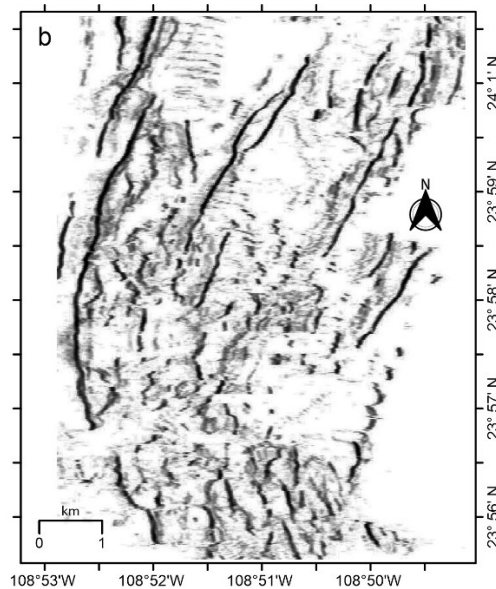


Figure 10.- Map showing the results of fault-line scarps using the 400 m window.

7.- Conclusions.

In general, it can be appreciated that our algorithm does a good job in differentiating fault-line scarps and cuestas associated with volcanic topography. However, even though our algorithm successfully detects most of the principal faults of length > 3 km, detection capability is function of window size and fault density. In Figure 10, it can be observed that the 400 m search window has the best fault scarp detection capability. We can appreciate this in the fault relay structure located at 108° 52' W 24° 1' N. This window size emphasizes the overlapping geometry of the faults and identifies the major faults, whereas other window sizes consistently miss elements of the structure. Other artifacts also appear with increasing window size, like a series of z-shaped features in the test area's southern part. Also, our algorithm could not detect a series of closely spaced faults in the footwall block of the longest fault of the bounding relay structure, despite having the secondary fault array a fairly good morphological expression. By contrast, our algorithm resolves fairly well a series of isolated faults on the northeastern side of the basin of similar geomorphological expression.

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