2D Resistivity Characterization of Alluvial Deposits near Azuero Fault, Panama

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Abstract

Recent alluvial deposits adjacent to the Azuero-Soná fault zone, at Azuero peninsula, Panama, are inspected with resistivity measurements in order to find narrow vertical ruptures parallel to the main strike of the fault, which could indicate neotectonic activity. Five 2D resistivity sections at three locations, Malena, Sapotal and Quebro, were obtained with semiDemo version of RES2DINV software through six lines of data acquisition: two lines taken at the same location were merged into one. Profiles at Sapotal and Quebro show low resistivity elongated zones (1.40 Ωm at Sapotal and 45.7 – 57.3 Ωm at Quebro) which indicate percolation of fluids in vertical structures. These structures are interpreted in this study as a product of neotectonic activity of Azuero fault. Inferred ruptures reach depths of 3.13 m at Sapotal and 1 and 5 m at Quebro. At Quebro, a previous GPR survey shows the same vertical structure found with resistivity. Using orientations of both resistivity and GPR profiles, a rupture direction of ~98° is obtained, nearly parallel to the main strike of Azuero fault (120°). The orientation of this structure corresponds to a counterclockwise synthetic structure in the Riedel shear zone of the Azuero Soná fault zone. Also, a model of generation of the terraces is proposed: at Sapotal an erosional-depositional event of a tributary created two terraces while at Quebro one tectonic response and a climatic event, which changed the river course, created three terraces.

1. Introduction

1.1 Objectives and relevance of the study

Several studies have taken place in Panama in order to make tectonic reconstructions. Research has been focused specifically in San Blas-Darien, Sapo and Majé massifs (eastern Panama), Limon and Pedro Miguel faults (central Panama) and Burica peninsula (western edge of Panama). Neotectonics, geomorphology, stratigraphy and satellite imagery analysis were used to establish a tectonic setting since Late Cretaceous (Mann, 2007, Morell et al., 2011 y Rockwell et al., 2010). However, Azuero-Soná fault zone (ASFZ) at Azuero peninsula (AFZ) is poorly known. The Azuero Fault (AF) is a left-lateral strike-slip fault (Mann & Burke, 1990) and active strike-slip faults, such as Haiyuan Fault in the Tibetan plateau and San Andreas Fault in United States, create ruptures sub-parallel to the mean strike of the fault (Qidong et al., 1986 and Li & Fares, 1986). Also, superficial faulting in strike slips is extensively subjected to the climate. According to the Environmental Authority of Panama (ANAP) average annual rainfall in Azuero Peninsula is 1000 – 1500 mm, which facilitates loss of superficial information. Therefore, it is highly probable that the ruptures remain in the subsurface, where erosion and weathering are less aggressive, and these can be found using a geoelectric method.

The idea behind this study is to complement existing literature on the geometry and kinematics of ASFZ, and encourage new research on the topic. It is expected that this study will give rise to tectonic models for the internal deformation of Panama, geodynamic models of the rock rheology along the fault, derived from geodesy measurements and analysis, and evaluation of the seismic hazard. In this study, resistivity, a geophysical method, and field observations are combined to provide constraints in the neotectonic activity of ASFZ by detecting covered fault offsets in a humid climate environment.
In an attempt to establish if the ASFZ presents neotectonic activity, resistivity measurements were taken in Quaternary deposits near the fault in Azuero peninsula. In the search for ruptures parallel to the AF, resistivity profiles were oriented perpendicular to the structure, at the south-western part of the peninsula. The purpose of AFZ characterization through geoelectric surveys, and the main objective of this study, is to determine if the geologic structure is active. In order to accomplish the purpose, this study presents first a conceptual framework about resistivity method, second a literature review about neotectonics of the Caribbean and Azuero peninsula and third the results and analysis where maps and stratigraphy of the terraces and the resistivity sections are presented and discussed.

1.2 Location of the study zone

Azuero and Soná peninsulas are located in western Panama extending southward into the Pacific Ocean (Fig. 1). They comprise the eastern boundary of the Gulf of Chiriquí and the western boundary of the Gulf of Panama, and are separated from each other by the Gulf of Montijo (Fig. 1). Highlands of both peninsulas are divided by a prominent lineament which extends into westernmost Panama; the ASFZ which is over 300 km long (Fig. 1). It strikes 120° and suggests a 40-km-wide zone of fault related deformation parallel to the main lineament of the fault (Mann & Corrigan, 1990).

The study zone is located in the western part of the Azuero peninsula. It is divided into three sectors: Sapotal, Malena and Quebro, called as the townships Sapotal, Malena and Quebro, in Veraguas province.

![Figure 1. Azuero peninsula delimited by the Gulf of Panama and Gulf of Montijo and extending southeastern into the Pacific Ocean. Azuero Soná fault zone represented as a dotted red line crossing Soná and Azuero peninsulas.](image-url)
2. Electrical resistivity imaging in 2D and neotectonics

2.1 Electrical properties of rocks

Geolectric methods are based on interpreting different lithology and structures in the ground using resistivity variations. Using Ohm’s law, $V = IR$, where $V$ is voltage or potential, $I$ current and $R$ resistance, resistivity can be measured if a current passes through a material. Current can spread in rocks and minerals in three different ways: ohmic conduction, electrolytic conduction and dielectric conduction. In the first, electrons flow freely inside crystalline structure of a material. In the second, current flows through ions of saline solutions contained inside pores. And in the third, electrons in the crystalline structure of a material move with respect to the nucleus dividing positive and negative charges (dielectric polarization) and a displacement current is produced. This is because there is no flux of charged particles along macroscopic distances, but changing the position of ions causes a current. A displacement current would be present if rocks had no interconnected pores with fluids inside them: rocks are bad conductors themselves. Therefore, spread of the current in rocks is due to electrolytic conduction. The latter is influenced by mobility, concentration and dissociation of ions, which depends on the quantity and conductivity of sulphides and chlorides, and to a lesser extent on geometry of the interstices.

Because materials retard current flux, energy is necessary to move charges. Thus, the resistivity prospecting method provides measurement of this property to distinguish lithology and structures in the ground. Figure 2 shows resistivity value ranges of different lithology.

2.2 Resistivity methods

Resistivity methods consist of introducing current into the ground through point electrodes, measuring potential $V$ at other point electrodes and determining effective or apparent resistivity of the subsurface (Telford et al., 1990). Quantitative results of the resistivity technique are obtained by using an electrode configuration with specific dimensions.

![Figure 2. Typical ranges of apparent resistivity for earth materials. Contrast between water (salt or fresh) and unconsolidated sediments (clay, gravel and sand) are used to locate ruptures in the alluvial deposits. Taken from Palacky (1988).](image-url)
2.2.1 Two current electrodes at surface

First, a single current electrode at depth (mise-à-la-masse method) is taken into account. The potential \( V \), as a function of the distance \( r \) from the current electrode is (Telford et al., 1990)

\[
V = -\frac{A}{r}
\]

where \( A \) is an integration constant. The equation is obtained through double integration of the Laplace’s equation in spherical coordinates. The second constant of integration is zero because \( V = 0 \) when \( r \to \infty \). Equipotential surfaces are spherical thus the current crossing one of it is (Telford et al., 1990)

\[
I = A_sJ
\]

where \( A_s \) is the area of the sphere. \( J \) is the current density, defined through Ohm’s law as

\[
J = \sigma E
\]

where \( \sigma \) is the conductivity of the medium and \( E \) is the electric field. The latter is the negative gradient of the potential, then

\[
I = 4\pi r^2 J = 4\pi r^2 \sigma E = -4\pi \sigma \frac{dV}{dr} = -4\pi \sigma A
\]

In a half-space, a point electrode located at the surface of a medium with uniform resistivity \( \rho \) with air above \( (\sigma = 0) \), generates equipotential surfaces as half spheres (Fig. 3). Hence, the current crossing one of these surfaces is

\[
I = -2\pi \sigma A
\]

When two current and two potential electrodes are in a half-space (Fig. 4), then

\[
V_1 = -\frac{A_1}{r_1} \text{ and } V_2 = -\frac{A_2}{r_2}
\]

The direction of the current is opposite, but its magnitude is equal at the electrodes, thus

\[
A_2 = -A_1 = -\frac{l\rho}{2\pi}
\]

For three electrodes, two current electrodes and one potential electrode, the potential is

\[
V_1 + V_2 = \frac{l\rho}{2\pi} \left( \frac{1}{r_1} - \frac{1}{r_2} \right)
\]

and for one more potential electrode, the difference in potential is

\[
\Delta V = \frac{l\rho}{2\pi} \left[ \left( \frac{1}{r_1} - \frac{1}{r_2} \right) - \left( \frac{1}{r_3} - \frac{1}{r_4} \right) \right]
\]
This arrangement corresponds to the one used to measure resistivity in Quaternary deposits near ASFZ at Azuero peninsula.

![Figure 3](image3.png)

**Figure 3.** Point source of current at the surface of a homogeneous medium. Taken from Telford et al. (1990).

![Figure 4](image4.png)

**Figure 4.** Two current and two potential electrodes on the surface of homogeneous isotropic ground resistivity $\rho$. Taken from Telford et al. (1990).

### 2.2.2 Electrode array: Wenner-Schlumberger spread

The Wenner-Schlumberger array is a modification of the Wenner array, in which the distance between current electrodes and potential electrodes increases as a factor of $n$ times the distance between potential electrodes (Fig. 5). It was found that $\Delta V = \frac{1}{2\pi} \left[ \left( \frac{1}{r_1} - \frac{1}{r_2} \right) - \left( \frac{1}{r_3} - \frac{1}{r_4} \right) \right]$, thus

$$\rho = k \frac{\Delta V}{I}$$

where $k$ is the geometric factor of the array. From Figure 4 and Figure 5, this factor is equal to

$$k = 2\pi \left[ \frac{1}{nd} - \frac{1}{nd + d} \right]^{-1} = \frac{\pi n(n + 1)d}{d}$$

This indicates that the intensity of the signal varies inversely with the square root of $n$.

Wenner-Schlumberger array enables vertical and horizontal structures to be distinguished by setting $n \sim 1$ or $n \sim 6$, respectively (Fazzito, 2011).

![Figure 5](image5.png)

**Figure 5.** Electrode configuration in Wenner-Schlumberger array. $C_A$ and $C_B$ are current electrodes and $P_M$ and $P_N$ are potential electrodes. $d$ is the distance between potential electrodes and $nd$ is the distance between potential electrodes times the separation factor $n$. Modified from Telford et al. (1990).
2.3 RES2DINV

The program determines a two-dimensional (2D) resistivity model for the subsurface using acquired electrical data. The inversion is carried out applying a model that consists of a large number of rectangular blocks. The distribution and size of the blocks are setting by the program based on the distribution of the data points. The depth of the last row of blocks is set to be approximately the median depth of investigation. A finite-element subroutine calculates the apparent resistivity values and a non-linear smoothness-constrained least-squares optimization estimates the resistivity of the blocks. This method is based on the following equation:

\[(J^T J + \lambda F) \Delta q_k = J^T g - \lambda F q_k\]

where

\[F = \alpha_x C_x^T C_x + \alpha_z C_z^T C_z\]

\[C_x = \text{horizontal roughness filters}, C_z = \text{vertical roughness filter}\]

\[J = \text{jacobian matrix of partial derivatives}, J^T = \text{transpose of } J\]

\[\lambda = \text{damping factor}\]

\[q = \text{model change vector}\]

\[g = \text{data misfit vector}\]

The damping factor and roughness filters can be adjusted to different types of data. The smoothness constraints are used by the optimization method to reduce the difference between calculated and measured resistivity. The root-mean-squared (RMS) error is used to calculate this difference which has not necessarily been the lowest to obtain the best geological model. Generally, between the third and fifth iterations the RMS does not change significantly and at this point the model is a prudent approach.

The data have to be stored in DAT format containing the name of survey line, unit electrode spacing, array type (7 for Wenner-Schlumberger), number of data points, type of x-location for data point (1 for mid-point), flag for induced polarization data (1 if present) and location, electrode spacing (a), n factor and apparent resistivity value for each point (tables 1 – 6).

The vertical to horizontal flatness filter ratio (VHFFR) is a parameter that allows the user to produce models elongated vertically or horizontally. The first model is obtained by setting VHFFR greater than 1, and the second by setting it less than 1. The program allows values between 0.01 and 4.00 and the default value is 1.00. As the main purpose of this study is identify narrow ruptures in Quaternary deposits, this parameter was modified from 1.00 to 4.00 to optimize the inversion criterion for vertical structures. The model refinement was also used to obtained resistivity variations in narrower cells (model cells with widths of half the unit electrode spacing). Other parameters were left as default setting.

2.4 Neotectonics

Earth scientists use the term neotectonics to divide tectonic history before and after the last major tectonic change in an area of study (Van Hinsbergen, 2011), and as every area of study has behaved differently to other, authors use different definitions based on the age and the tectonic context where the events have taken place. About changes in tectonic context from one study zone to another, Becker (1993) wrote that:
“The ‘neotectonic period’ is the youngest period of tectonic activity and extends up to the present. The beginning of the neotectonic period during the Cenozoic may be regarded as having begun when characteristic changes in the tectonic evolution of a region of interest have occurred for the last time. Changes in the different tectonic facets, which characterize the evolution of a region, need not to be simultaneous, and hence the times of the last change may differ between facets. This leads to the definition of a ‘transitional time interval’ […] whose length depends on the regional geological evolution. When a broad transitional time interval exists, the beginning of the neotectonic period may be defined as the earliest time marker by when most of the characteristic changes of the tectonic evolution of the region had occurred.”

One of the attempts in restricting the period of neotectonic activity was made by Manzoni (1968) who defines neotectonics as the study of rock deformation and dislocation during the Late Tertiary and the Quaternary. Other authors such as Angelier (1976) do not restrict neotectonics to a period of time and explain that neotectonics is “the period in which we can extrapolate geophysical observations in the light of geological data”. In this regard, van Hinsbergen (2011) argues that defining a period as ‘neotectonic’ require very clear definitions to avoid confusion arising from the use of this terminology as a regional correlation tool.

Neotectonics have been widely developed during the last decades as a result of scientific advances such as satellite laser (Vita-Finzi, 1986). These kinds of survey techniques allowed geophysicists and geodesists to measure displacements of the surface that cannot be detected without geophysical methods or highly precise monitoring advices such as GPS, strainmeters, tiltmeters and radars, due to the nature and rate of the movements.

Research into the subject was developed because a preliminary study of present phenomena allow geologists to establish the role of past phenomena, and in the case of tectonic deformations this hardly applies because demonstrate a movement directly is very limited (Goguel, 1962). Then, in many parts of the world neotectonics was being actively used to study phenomena such as isostatic rebound due to deglaciation, ground deformation due to earthquakes and the seismic cycle.

Neotectonic activity can be detected by mapping geomorphological features and processing of geophysical and geodetic data. Changes in geomorphology can be detected by analyzing successive topographic maps or LANDSAT imagery. This is especially useful to study events of big magnitude, such earthquakes, or to study well recorded long-term events, such as plate boundary deformations. For example, in Algeria, two successive topographic maps were used to put in evidence that El Asnam earthquake had been accompanied by warping of the valley floor (Vita-Finzi, 1986). However, when the rate of deformation is low or when there are not instrumental records of the event, highly accurate geodetic methods and geophysical surveys are highly valuable. Geodetic measurements focus on tracing crustal movements which are currently taking place. Geodetic measurement tools include strainmeters and tiltmeters, and more recently GPS and radar imagery. These tools have been used to study coastal uplift and submergence, interseismic deformation, post-seismic transients, isostatic adjustments and volcano deformations due to magma movement. On the other hand, geophysical methods such as Ground Penetrating Radar, seismic and resistivity have been used to inspect the subsurface in the search of structures that remain only in the stratigraphic record because the event did not generate geomorphological features or they eroded.
2.5 Equipment and field procedure

Prior to resistivity data collection, Quaternary deposits were recognized through satellite imagery inspection with Google Earth. Their localization was corroborated with cartography later in the field work.

Three weeks of field work were conducted in order to corroborate the location of Quaternary deposits near the AFZ and establish suitable places in which resistivity measurements could be made. Three localities were chosen to acquire resistivity data: Sapotal, Quebro and Malena. In Sapotal, three resistivity profiles were obtained by measuring four times: two times the first line, and a single time the other two. In Quebro and Malena was obtained one profile per location.

Field work was divided between resistivity data acquisition and cartography of the geomorphic and structural features, Quaternary deposits and lithology near the fault. Six days were spent in resistivity measurements and thirteen days in cartography. The latter was carried out where rivers and sea cut the rocks and expose lithology: Rio Torio, Playa Malena and Rio Sapotal.

The components for making resistivity measurements are power source, cables, meters for measuring distance, current and voltage, electrodes and reels. The power source used in this study was two car batteries connected in series. To avoid effects of electrolytic polarization, the dc polarity was reversed periodically (in each measurement) by hand shifting cables connected to poles of the battery. Metal electrodes were 40 cm long. Telford et al., 1990, recommend electrodes of 50 cm long for good electrical contact. In compensation, the contact was improved due to wet ground. Also, the electrodes were always collinear to make interpretation of results and field work easier.

Six resistivity profiles were obtained in Sapotal, Quebro and Malena where changes in dielectric permittivity and conductivity were evidenced by discontinuities in Ground Penetrating Radar (GPR) reflectors (Revelo, 2015). The resistivity in the six profiles was acquired using Wenner-Schlumberger array with separation between dipoles of 1 to 4 m and separation factors (n) of 1 to 9. This electrode array was chosen over Wenner array because the latter is more sensible to vertical variations in resistivity, hampering the solving of the narrow vertical ruptures. Likewise, Wenner-Schlumberger array was chosen over dipole-dipole array considering that the geometric factor of the first \( k = \pi n(n + 1)d \) makes the intensity of the signal inversely proportional in relation to the square of n, while in the second \( k = \pi n(n + 1)(n + 2)d \) the intensity of the signal is inversely proportional to the third power of n; therefore, the intensity of the signal is higher in Wenner-Schlumberger array. Additionally, Wenner-Schlumberger array enables vertical and horizontal structures to be distinguished by setting \( n \sim 1 \) or \( n \sim 6 \), respectively (Fazzito, 2011).

The lengths of the profiles are 11, 14, 16, 19, 22 and 29 m, with which a maximum inspection depth of 14 m can be reached. Apparent resistivity varies between 4 and 260 Ohm-m, typical values of non-consolidated alluvial deposits. Electrical wiring consisted of a 12 V car battery and cables connected to electrodes through which current was injected to the ground. Current and voltage were measured with digital multimeters Fluke 115 Compact True-RMS connected in parallel to the circuit. To avoid polarization effects and consequently errors in measurements, cables connected to the battery were systematically exchanged between positive and negative poles.
Stratigraphic columns of alluvials where resistivity data was acquired were digitized and are presented in the results section. Then, the pseudosections were obtained with the semiDemo version of RES2DINV software.

3 Geological and tectonic setting

3.1 Caribbean plate

At the present, the north boundary of the Caribbean plate are strike-slip faults allowing eastward movement relative to the North (Motagua-Polochic fault zone and the Oriente fault) and South American plates; eastward motion is accommodated by left-lateral faults along its northern edge and by right-lateral faults at the southern boundary. The northern plate boundary also presents north-south convergence (Fig. 6) with southward thrusting in Hispaniola due to divergence from Cuba and convergence with Hispaniola and Southeastern Bahamas (Ratschbacher et al., 1991). The valley of the Rio Motagua is the place where strike-slip faulting of the northwestern part is taking place (Guatemala and Honduras). North of Motagua-Polochic fault system is placed Maya block and at the south there is Chortis block. Oceanic lithosphere of the Americas is being subducted at the Lesser Antilles arc, and the oceanic lithosphere of the Cocos plate is being subducted along the western edge at the Middle American arc (Mann & Burke, 1984). Parallel to the active trench, a shear zone showing north-south extension and sinistral strike-slip deformation resulted from changes in tectonic setting during the Campanian – Oligocene (Ratschbacher et al., 1991).

The Caribbean plate is composed by borders of Cretaceous-Paleogene arc terrains about a central marine basin. Basaltic sills penetrated in the Venezuelan Basin, at ~80 Ma, making the Caribbean plate present anomalously thickness and buoyancy which resulted, both with the arc and continental land areas, in a complex deformation style at the recent times (Mann & Burke, 1984). Older faults also contribute to a more complicated tectonic setting because they act as lines of weakness and because silicate and feldspar-rich rocks of continents and island arcs deform more easily at low temperatures than do oceanic basalts (McKenzie, 1972).

Mann & Burke (1984) suggest that the neotectonic activity of the Caribbean plate started during Neogene or post-Oligocene times. They also indicate that many of the major faults may have not ruptured for over 200 years even though maps showing the distribution of earthquake epicenters indicate that earthquakes are common at widest. The distribution of the epicenters is located along the Middle America and Lesser Antilles subduction zones and transform-subduction zones of Puerto Rico and eastern Hispaniola, at the northeastern, and Trinidad at the southeastern Caribbean (Kafka & Weidner, 1981, Mann & Burke, 1984). Sykes et al. (1982) show a map of epicenters of earthquakes of the northern area of the plate demonstrating that at the strike-slip boundaries earthquakes are less common (Fig. 7). However, Sykes et al. (1982) also show that epicenters of earthquakes after 1900 forms a north-west belt parallel to the Oriente Fault Zone in Hispaniola and are concentrated also in Swan fault zone, at the northwest of the Caribbean plate, both strike-slip faults.

Strike-slip faults have a near relation with the historic seismicity of the Caribbean plate. Earthquakes along this kind of faults have been recorded since 16th century (Sykes et al., 1982). For example, in 1856 an earthquake along Swan Fault Zone caused a narrow and elongate zone of damage nearly parallel to the fault
Earthquakes have been recorded also at Jamaica occurred on the Septentrional Fault Zone and Enriquillo-Plantain Garden Fault Zone (Kelleher, 1973, McCann et al., 1979), strike-slip faults also. At the Lesser Antilles multiple episodes of tsunami impacts have taken place during the Younger Holocene (Scheffers, 2004). The historical record lists 88 tsunamis in the time period from 1489 to 1998 (Scheffers, 2004). O’Loughlin & Lander (2003) claim that there are six documented tsunamis in the northern Caribbean since 1492 and that four of these events occurred in the area of oblique collisional tectonics and larger historical earthquakes near Hispaniola and Puerto Rico. Also, Dolan & Mann (1998) indicate that the most widespread tsunami occurred in 1842 in association with a large strike-slip rupture on the plate boundary fault in Hispaniola.

![Figure 6](image)

**Figure 6.** Present geography and general tectonic of the Caribbean plate. Figure shows major and minor intra-plate trenches, ridges and transform boundaries. Taken from Pindell & Barrett (1990).

The movement direction of the Caribbean plate (18-20±3 mm/yr at the east relative to North America) implies that the segment of the plate boundary from northern Central America to southern Cuba is strike-slip with varying degrees of transtension and transpression. The maximum oblique convergence occurs between Hispaniola, where earthquakes and tsunamis were recorded. This plate motion is also partitioned onshore in strike-slip faults (Doland & Wald, 1998).

Mann & Burke (1984) report seven types of basins found along the lineaments of the Caribbean strike-slip faults: pull-apart, fault-wedge, fault angle and fault flank depressions, ramp valleys, depressions at oblique underthrusting and basins within secondary faults. 40 basins were analyzed by Mann & Burke (1984) most of all resulting in ages of Miocene and younger. Eocene and Oligocene basins show Neogene strike-slip displacements and can be found onshore.
3.2 Isthmus of Panama and Azuero peninsula

The Isthmus of Panama is part of the South Central American Arc and lies on the Panama Microplate. The isthmus is a southwestern extension of the Caribbean Plate that is in contact with the Chortis Block and presents an oblique subduction at the boundary with Nazca plate (Westbrook et al., 1995). Panama Microplate is limited by the Caribbean plate at the north, the Cocos and Nazca plates to the west and south, respectively, and the South American plate to the east.

Azuero peninsula is characterized by high relief which reflects the active tectonism of the southern Panama margin. On the other hand, central Panama presents a low topographic relief and highly weathered igneous and sedimentary rocks, representing a more stable intraplate tectonic setting with a lower rate of deformation (Cowan et al., 1998).

Caribbean plate boundary in Panama is different from the other boundaries because it has major strike-slip fault zones striking northwest, does not present calc-alkaline volcanoes and has a more complex earthquake pattern (Mann & Burke, 1984). As the neotectonics of Panama seems to be more complicated than other at the interior of the plate, the model of internal deformation proposed by Mann & Burke (1984) proposes that the symmetrical strike-slip displacements of continental and arc material away from South America, like the motion of Maracaibo Block, allow the presence of that complex behavior.

The prominent bend of the isthmus is attributed to gradual left-lateral slip on strike-slip faults trending northwest and minor right-lateral slip on faults trending northeast and extension of the Sambu and Medial basins (Mann & Burke, 1984).
First-motion studies made by Mann & Burke (1984) using focal mechanisms from Panama showed an east-west compression of the isthmus and right-lateral strike-slip motions in the Panama Fracture Zone. Focal mechanisms were also used to know the direction of maximum compressive stress. Kafka & Weidner (1981) derived a maximum compressive stress trending east-west, and Kellogg & Bonini (1982) obtained four zone of weakness directions in which the 090° maximum stress is releasing: 297°, 313°, 316 and 317°.

Mann & Burke (1984) suggest that the post-Miocene history of the isthmus seem to have been dominated by strike-slip faults nearly parallel to the Panama-Colombia border. Additionally, strike-slip faults are dominantly left-lateral and trend northwest (Mann & Burke, 1984). Some strike-slip faults are right-lateral and trend northeast, and appear to move triangular blocks of Panama northward relative to South America (Mann & Burke, 1984). Post-Miocene history of Panama has been governed by northwest to northeast movement of the isthmus away from the Colombia-Panama suture zone; strike-slip faults are not related to tectonic activity in the Pacific (Mann & Burke, 1984).

The tendency of strike-slip faults and overthrust lithosphere of the Caribbean plate suggest that the deformation of the isthmus could be related to the Neogene collision of Panama and South America (Mann & Burke, 1984). The convergent movement is, at the same time, accommodated by northwest-to-northeast strike slip motion and the subduction of the thinner (thicker if we consider it is oceanic lithosphere) Caribbean plate (Mann & Burke, 1984). These strike-slip faults also shift inwards developing local discontinuities along the fault trace, discontinuities that result in pull-apart basins and push-up segments (pressure ridges), very common in Panama strike-slip fault zones (Mann & Burke, 1984).

The South Panama Fault Zone accommodates deformation caused by the shortening between Nazca plate and Panama’s southern margin through large strike-slip faults such as the left-lateral Azuero-Soná Fault Zone (Cowan et al., 1998). The South Panama Fault Zone is thought to have ruptured in the early 20th century in 1904, 1913 and 1925 (Cowan et al., 1998). Trenkamp et al. (2002) estimate that the South Panama Deformation Belt accommodates 20-25 mm/yr of sinistral motion. Also, local shortening results in folding at a rate of maximum 1 mm/yr (Londsdale & Klitgord, 1978).

In central Panama, the Limon-Pedro Miguel fault zone shows right deflected channels displaced about 30 m in a 5 ka terrace, yielding a Holocene slip rate of 6 mm/yr (Rockwell et al., 2010b). Additionally, the authors demonstrate that Rio Gatún fault shows left-deflected largest streams of about 1-1.5 km, and minor drainages by tens to hundreds of meters. Comparing velocities from the CASA and CHEP GPS arrays Rockwell et al. (2010a) explain that western Panama stations are converging on Panama City by about 8 mm/yr and eastern Panama stations are getting away from Panama City at about the same rate.

del Guidice & Recchi (1969) made a local study in which they found that in the Azuero peninsula, folds are restricted to an immediate area due to the rigid behavior of the rocks comprising it. The existent folds are predominantly faulted monoclinals present in a faulted-blocks tectonic model described by Mann & Burke (1984). In the case of the AFZ, del Guidice & Recchi (1969) consider that the structure could represent the reactivation of an ancient fault related to the ultrabasic complex, due to the presence of pre-Eocene terrains (i.e. Ocú Fm. and the igneous basic-ultrabasic complex of the Mesozoic).
3.3 Previous geophysical and geomorphological studies of the ASFZ

3.3.1 Geomorphological characterization of strike-slip faults

Active faulting produce many landform elements such as fault scarps, warped and tilted ground, sag ponds and offset features (Fig. 8). Each kind of faulting creates an assemblage of landforms that can lead to the recognition of the presence of a structural feature and its classification (Keller & Pinter, 1996).

Strike-slip faults are considered to be important in two main tectonic settings: as a small structures (tens of kilometers) accommodating internal deformation and occurring in the upper levels of the crust, and as regional to continental extent called transform faults (Price & Cosgrove, 1990). In this section is made an emphasis on the first kind of structure and its geomorphological expressions.

A strike-slip fault can be recognized by coseismic surface displacement (e.g. 1906 San Francisco Earthquake along San Andreas Fault), by focal mechanisms and by physiographic features (Sylvestre, 1988). The characteristic assemblage of landforms caused by strike-slip faulting includes (Keller & Pinter, 1996, Sylvestre, 1988, Cloos, 1928, Riedel, 1929):

- **Linear valleys.** The most distinctive characteristic of an active strike-slip fault is its topographic linearity over tens of kilometers. Linear valleys develop because the rocks crush, making them more susceptible to weathering, due to the continuous movement along the main trace of the fault.
- **Deflected streams.** These features are described as an oblique stream that enters to the fault zone and flows parallel to the main trace before continue its initial direction flow.
- **Fault scarps.** These are topographic reliefs resulting from a vertical displacement due to a normal or inverse component of the fault or by extension, resulting in two parallel scarps. The height of a fault scarp could indicate the minimum vertical displacement of the fault, but not necessarily since the vertical component could vary along the trace or the topography is rugged.
- **Offset streams.** These are streams displaced by faulting, and unlike deflected streams they indicate the direction of relative movement. The stream may erode a more direct route to the fault zone producing a beheaded stream at the fault trace.
- **Shutter ridges.** This morphology is produced when the fault displaces a ridge from one side to a trench on the other side.
- **Sag ponds.** When a downwarping between two branches of the fault, a gully is formed.
- **Springs.** These are barriers or conduits of the groundwater made by crushed rock.
- **Benches.** They are elevated and flat topography, which could be warped, produced by displacement along local segments of the fault.
- **Pressure ridges.** They are formed by compression where the fault is not straight; between multiple traces of the fault.
- **Riedel shear structures.** These are subsidiary shear fractures that propagate at a short distance of the main fault but are coeval with it. The Riedel pattern consists of conjugate shear bands arranged in en-échelon arrays and denoted by R (synthetic) and R’ (antithetic). These R and R’ bands create an angle of $\phi/2$ and 90- $\phi/2$ to the principal shear zone (Fig. 8b).
3.3.2 Previous studies of the ASFZ

The Azuero fault zone is a northwest striking left-lateral fault zone that can be traced 150 km from the southeastern coast of the Azuero Peninsula (Fig. 1) to the northwestern coast of the Soná Peninsula (Mann & Corrigan, 1990). The ASFZ may extend offshore until the South Panama deformed belt as well as the Southern Panama fault zone (Westbrook et al., 1995). Its length is 196 km from end-to-end and it has a cumulative length of 251 km (Cowan et al., 1998). Also, it is nearly subvertical and striking N 61° W ± 6° (Cowan et al., 1998).

Figure 9 shows a seismicity map of Central America which exhibits up to Ms = 8 earthquakes occurred at the Azuero fault. Bundschuh & Alvarado (2007) mention that ASFZ experienced a strong earthquake in 1943, one of the most catastrophic events in Central America since 1900. Molnar & Sykes (1969) also report that earthquakes occurred between 1954 and 1962 along AFZ are less than 70 km in depth. MacKay & Moore (1990) remark that the majority of earthquakes presented depths less than 33 km.

Muñoz (1988) evaluate the seismic hazard in Panama using seismotectonic regionalization. Muñoz (1988) uses a probabilistic approach to define the probability of an earthquake at a given place and within a time of period using epicenters, magnitude, intensity at a source and an estimation of peak ground acceleration, as well as the adoption of the Poisson stochastic model.

To apply this model, Muñoz (1988) made the following assumptions: (1) earthquakes are spatially independent, (2) earthquakes are temporally independent and (3) the probability of two events occurring at the same location and the same time is close to zero. Probability of occurrence vs. magnitude graph (Fig. 10) shows that Azuero block has a small probability (less than 0.2) of experience an earthquake of MM = 8 between 1988 and 2038. However, the probability of experience an earthquake between that time interval
is greater for earthquakes of magnitudes ranging from 6 and 8, being 1 the probability of a MM = 5 earthquake occurrence.

Thus, Muñoz (1988) conclude that the probabilistic seismic hazard is lowest for Azuero block being capable of produce an MM = 7 earthquake in about 160 years. Complementing, Muñoz (1990) produces a probabilistic Seismic Hazard Maps for the return period of 50 yr (Fig. 11) and conclude that Azuero province could have a maximum MM intensity of VII.

Figure 9. Seismicity of Panama from 1505 to 1992. Taken from Montero et al. (2011)

Rockwell et al. (2010a) propose a soft block indenter model to explain that the collision of Central America and South America resulted in a high degree of internal deformation. The authors assume, based on Panamanian major faults map that the fault zones extend and interconnect at some point (Fig. 13). They use available GPS slip rates for central Panamanian faults and assume a slip rate in areas of no GPS measurements such that the non-brittle deformation is minimum.

For the Middle American Trench Rockwell et al. (2010a) use a rate of 90 mm/yr, for Colombia-Ecuador trench a rate of 50 mm/yr, for the South Panama Deformation Belt a rate of 26 mm/yr and for the Rio Gatún fault and Pedro Miguel-Limón fault zone a rate of 5 mm/yr. In this model the internal deformation is being accommodated by strike-slip faulting (slip in Pedro-Limón and Gatún faults) due to convergence between Nazca and Central America plates and rotation of the Isthmus of Panama resulting in left-lateral slip in Darien region, and overriding of Panama block over Caribbean seafloor.

The authors made an estimation of how much internal deformation have been accommodated within Panama major fault zones, and conclude that Panama has accommodated at least 70 km of deformation in the last 3 Ma.

The model assumes that there is no vertical rotation axis because the GPS coverage is insufficient to determine both vertical and 2D horizontal rotation (Rockwell et al., 2010a). Another assumption is that
strike-slip faults are horizontal and blocked at a depth of 15 km, and that the ones within Panama are slipping at a rate determined with paleoseismology.

The model infers fault slip rates that cannot be measured with GPS, but need to be consistent with the ones obtained by geodetic data. Rockwell et al. (2010a) deduce that AFZ in southwestern Panama has a largest left-lateral strike-slip of 5 to 7 ± 2 mm/yr. This slip rate corresponds approximately to the motion between Azuero peninsula and Panama City (Trenkamp et al., 2002). However the peninsula motion relative to Darien region is near to zero (Trenkamp et al., 2002). This is explained by Rockwell et al. (2010) model because the triangular Azuero block delimited at the southwest by the Pedro Miguel fault is being extruded southwestward resulting in shortening in the South Panama Deformed Belt.

One of the geomorphological expressions of the high movement rate of the Azuero fault is a left-deflected stream identified by Rockwell et al. (2010a) in an air photo of Rio Quebro near Cañablanca and Las Bocas (Fig. 14). In this figure, Rockwell et al. (2010) also observed a left-lateral displaced alluvial fan.

Geophysical methods have been used also to test the neotectonic activity of the AFZ. Revelo (2015) analyzed GPR data from recent alluvial deposits near the fault at three localities: Playa Malena, Rio Sapotal and Rio Quebro. These locations were chosen by the examination of satellite imagery.

The deposits were composed by unconsolidated sediments in which 29 transects were made: 5 surveys in Rio Quebro, 14 surveys in Rio Sapotal and 9 surveys in Playa Malena. Lengths of these profiles varied from 40 to 250 m in Quebro, 30 m in Sapotal and 40 to 100 m in Malena.

Transects of interest were the ones made perpendicular to the strike of the fault in which vertical ruptures could be recognized and neotectonic activity could be corroborated. The data was acquired along linear paths and flat parts of the terraces in order to minimize the topography effect and the difficulty of the interpretation.

One of the difficulties presented when acquiring the data was the heavy rains the days before GPR surveys. Revelo (2015) explains that the penetration depth of the GPR signal depends on the water content on the subsurface and, as the rain saturates the ground, some profiles were affected by the high water content.

At Quebro, vertical discontinuities on the horizontal layers were found (Fig. 15), and are inferred to be, by Revelo (2015), due to a vertical rupture. The layers affected by this structure are the shallower ones meaning that the deposition of the youngest sediments occurred before the last rupture. A discontinuity in the lower layers was also identified 10 m at the east of the previous survey by another GPR profile.

At Malena and Sapotal, Revelo (2015) did not found any evidence of vertical ruptures in the GPR data. He attributes those results to the water saturation which made impossible the establishment of concluding evidence that neotectonic activity is currently affecting those areas.
Figure 10. Probability of earthquake occurrences with a range of magnitudes in 50 years for Azuero, the Panama deformed belt (PDB), the Panama fracture zone (PFZ) and the Panama suture zone (PSZ). Taken from Muñoz (1989).

Figure 11. Contour map showing iso-intensity earthquake curves for Panama. Taken from Muñoz (1990).

Figure 12. Map of Quaternary folds and faults of Panama. Taken from Cowan et al. (1998).
Figure 13. Panama neotectonic blocks inferred with geodesy measurements major faults slip rates. Taken from Rockwell et al. (2010a).

Figure 14. Azuero Soná fault zone in Azuero peninsula represented as a red dotted line. Rio Quebro and an alluvial fan are left-deflected. Taken from Rockwell et al. (2010a).
Pérez-Ángel (2015) presents a structural characterization of the AFZ in which three samples are analyzed, a pseudotachyllite and two phyllonites. The study of these samples by stereonet analysis shows a dextral shear sense of the fault and two events of deformation: the one that produced phyllonites and the event that produced the pseudotachyllites. Pérez-Ángel (2015) claims that AFZ is approximately 2 km wide in which is evidenced the brittle zone of the fault (fault breccia, cataclasite, basalt, sedimentary breccia, limestone and gabbro), the ductile zone (Ocú Fm. and phyllonites) and a less deformed zone comprised by igneous bodies (Fig. 16).

4. Results

4.1. Maps of recent deposits

Recent deposits at Azuero peninsula were located using Google Earth, and three localities near AF were chosen to conduct resistivity surveys: Malena, Sapotal and Quebro. Figures 17 and 18 shows deposits at Azuero peninsula delimited with Google Earth, deposits mapped at the field work and the three localities where resistivity data was acquired.
These deposits were recognized based on their flat topography and lack of vegetation; these areas are used mainly to agricultural purposes. Then, suitable areas in which conduct resistivity measurements were located depending on the proximity to the campsite and the availability of access roads. These locations were evaluated at the fieldwork, and the exact places were chosen there taking into account, both the roads and proximity to the campsite, but also the weather and the adjacency to the fault.

At the deposits location, lines where resistivity data was going to be acquired were chosen to be perpendicular to the main strike of AF and in flat areas to simplify the post-processing of the data. Thus, at Malena the measurements were taken at a football field, and at Sapotal and Quebro the measurements were taken in parts of the deposits where the topography did not change abruptly. However, in Sapotal and Quebro the deposits were gently tilted.

Taking into account the slope of the deposits, the same as the elevation and extension, alluvial deposits at Quebro and Sapotal were differentiated based on their relative age. Two deposits at each location have been differentiated and mapped. At Sapotal these deposits are parallel and at Quebro one of the deposits encloses the other. The undifferentiated deposits are the ones recognized by Google Earth inspection and whose limits cannot have been established in the fieldwork.

![Figure 16](image.png)

*Figure 16.* Cross section of the AFZ in the western-central area of the Azuero peninsula. There are portrayed the three main zones of the fault: brittle zone, ductile zone and less deformed zone. Modified from Pérez-Ángel (2015).
Figure 17. Quaternary deposits at Azuero peninsula. Red boxes indicate deposits studied in this work.
Figure 18. Study zones located in Figure 18. a. Malena. b. Sapotal. c. Quebro.
Figure 19. Recent alluvial deposit at Malena. Resistivity measurements were made perpendicular to the main trace of the AFZ. Taken from Revelo (2015).

4.2. Stratigraphy of recent deposits

Stratigraphic columns of recent deposits (Figs. 20, 21 and 23) show mud, sand and gravel lithology ranging in grain size from silt to cobble.

At Malena 1.40 m of mud and gravel comprise the deposit where clasts of gravel are rounded and low spherical basalts (Fig. 20). Roots were found in mudstone which lies over 70 cm of coarse gravel. The deposit is highly weathered.

At Sapotal, an outcrop of 2.6 m shows a sequence of gravel and sand over mud and sand (Figs. 21 and 22). The sediments are highly weathered and at the top they are completely weathered (gravel is transformed into soil). Gravel clasts are sub-rounded and poorly sorted, and its content respect to the sandy matrix increases to the top: lower stratigraphic bed has a content of 60% clasts while upper stratigraphic beds have 80% clasts. Sand was observed in this outcrop unlike outcrops at Malena and Quebro.

At Quebro, mud and gravel comprise a thick deposit (15 m) where intercalations of these two lithologies are present along all the sequence (Fig. 23). At the top, beds are thinner than at the bottom. Gravel clasts are embedded in a sandy matrix which comprises 40% of the bed. The younger deposit corresponds to the first 2 m.
Stratigraphy of the recent deposits was complemented with geologic observations in antique rocks. Geologic observations were made at Playa Malena, Rio Torio, Rio Sapotal, Quebrada Salitre and Rio Higueronoso.

Two places are of especial interest: Playa Malena and Quebrada Salitre. In Playa Malena, local folds in the fault zone are present, ranging from 10 to 30 m in length. Synclines, anticlines and inverse faults are reported. In this location Ocú limestones and Cenozoic mudstones outcrop over lithoarenite and matrix-supported conglomerate intercalated with mudstone. Both units are widely fractured preferentially in east-west directions (nearly parallel to the main strike of AFZ). Towards south-east direction a vertical fault breccia of about 10 m thickness is enclosed by fault gouge recognized by aligned clay minerals. It is in contact with basalts and calcareous lithoarenites. In Quebrada Salitre a broadly deformed Ocú Fm. is exhibited, where anticlines and synclines are faulted and rocks show a large amount of fractures.

Also, two pressure ridges were inferred using Google Earth imagery (Fig. 24). They were recognized by their elongated shape and steep slopes using the elevation profile tool in Google Earth. The first inferred pressure ridge is located at Malena, between two recent deposits. It was recognized using an image of the year 1969 because the 2012 image presents cloudiness. It is 860 m long and 600 m wide and it is not within the main strike of the AF. The second inferred pressure ridge is at El Pilon in Los Santos province, approximately midway of the AF. It was recognized in 1969 and 2012 Google Earth images. It is 12 km long and 3 km wide. This last inferred pressure ridge seems to be deflected at its ends: to the north, perpendicular to the fault, at its eastern edge and to the south, perpendicular to the fault, at its western edge.

![Figure 20. Stratigraphic column of Malena alluvial deposit showing a sequence of gravel and mud. Roots were found inside mud bed.](image-url)
Figure 21. Stratigraphic column of Sapotal alluvial deposit showing a coarsening upward sequence starting at the bottom with silt sized muddy sediments and finishing at the top with granule sized gravel clasts embedded in a sandy matrix.

Figure 22. Recent deposit at Sapotal. The outcrop shows the alluvial sequence recorded at the stratigraphic column in Figure 30.

Figure 23. Stratigraphic column of Quebro alluvial deposit showing a sequence of gravel and mud. An intercalation of thin beds was seen at the top. Clasts comprise 60% of the gravel beds.
4.3. Resistivity data inversion

Five resistivity models were obtained after the data inversion. Line 1 of Sapotal was measured two times in the field (Table 1 and Table 2) and is presented as a single model. RES2DINV allows constructing a single resistivity profile with at least two time series in the option “Time-lapse data”. The other four models were acquired in a single data collection thus the time-lapse option was not required. The option was used in all five models to make cells vertically narrower leading to a unit electrode spacing of 0.500 m. The ruptures are placed where resistivity values are the lowest. At the ending of the profiles ruptures are not inferred due to the uncertainty of the resistivity values enclosing the low-resistivity areas.

Maximum depth of investigation is approximately one half of the horizontal length. Data points with anomalous apparent resistivity (Sapotal 3 point with resistivity of 2440 Ωm and Sapotal 1 point with resistivity of 0 Ωm) were eliminated to facilitate the interpretation process.

The damping factors were established as 0.1500 for the initial damping factor, 0.0200 for the minimum damping factor and 5.000 for the first layer damping factor. As the measurements became noisier with depth the damping factor increased by 1.050 with each deeper layer. The thicknesses of the layers were set as 0.3750 of the unit electrode spacing for the first layer and 1.100 of the layer above.

To optimize the inversion parameters for vertical structures, the vertical-to-horizontal flatness filter ratio was incremented from 1.00 to 4.00.
The semiDemo version of RES2DINV allows 3 iterations for the least-squares inversion subroutine, thus the absolute error could not be reduced for Sapotal 1 model below 23.5%, but in the other five profiles absolute errors ranged between 0.3 and 5.4%. The program did not detect unusually high or low resistivity values produced by the inversion. However, the blocks at the sides and bottom have a relatively large effect on the inversion process compared with the neighboring blocks resulting in unusually low or high resistivity values in the bottom corners. This effect was reduced by setting blocks with the same widths.

Malena 1 resistivity profile (Fig. 25) presents apparent resistivities ranging from 25.6 and 39.9 Ωm and a maximum depth of investigation of 4.99 m. A low resistivity block is observed between 5 and 11 m and the southwest more resistivity sediments are deposited.

Figure 25. Malena profile showing resistivity values between 25.6 and 39.9 Ωm.

In Sapotal 1 resistivity profile (Fig. 26), apparent resistivity varies between 1.40 and 184 Ωm and the measurements reach a depth of 12.1 m. On the surface, between 24.5 and 25 m it can be seen a low resistivity zone of approximately 3.13 m of depth. Between 5 and 7 m a high resistivity block (184 Ωm) is enclosed by sediments with lower resistivity (91.6 Ωm).

In Sapotal 2 resistivity profile (Fig. 27), apparent resistivity is between 47.1 and 97.7 Ωm and the profile reaches a depth of 8.47 m. A block of nearly homogeneous resistivity (60.6 – 68.5 Ωm) is situated between 5 and 18 m enclosed by a low resistivity feature at the southwest and a high resistivity feature at the northeast. No low resistivity zones are observed in this profile.

Sapotal 3 resistivity profile (Fig. 28) shows apparent resistivity varying between 31.4 and 78.0 Ωm and 9.56 m as a maximum depth of investigation. A homogeneous block of high resistivity (78.0 Ωm) is placed between 9 m and 18 m and sediments with low resistivity are at the beginning and end of the model. No low resistivity zones are observed in this profile.

Figure 26. Sapotal line L1 showing an elongated low-resistivity zone at 24.5 m. Variations in resistivity are between 1.40 and 184 Ωm and the low resistivity zone has values between 1.40 and 2.82 Ωm.
Figure 27. Sapotal L2 showing variations in resistivity between 42.1 and 98.7 \( \Omega \)m.

Figure 28. Sapotal L3 showing resistivity values between 31.4 and 78.8 \( \Omega \)m in a nearly homogeneous block.

Apparent resistivity of Quebro 1 resistivity profile (Fig. 29) varies between 45.7 and 101 \( \Omega \)m and the maximum depth of investigation is 6.56 m. Two low resistivity zones are located at approximately 2.5 m and 15.5 m with resistivities of 57.3 \( \Omega \)m and 45.7 \( \Omega \)m respectively. These zones have lengths of 1 and 5 m approximately. A high resistivity block (101 \( \Omega \)m) is placed between 7.5 and 10.5 m and it is enclosed by low resistivity sediments both southwest and northeast.

Figure 29. Quebro line displaying resistivity variations between 45.7 and 101 \( \Omega \)m. The profile displays two low resistivity zones: one at 15.5 m (45.7 \( \Omega \)m) and the other at 2.5 m (57.3 \( \Omega \)m).
Table 1. Sapotal 1_1 resistivity measurements. C1 and C2 are positions of current electrodes and P1 and P2 are potential electrodes relative to the start of the profile. AB/2 is half of the distance between current electrodes and MN is the distance between potential electrodes.

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Table 2. Sapotal 1_2 resistivity measurements. C1 and C2 are positions of current electrodes and P1 and P2 are potential electrodes relative to the start of the profile. AB/2 is half of the distance between current electrodes and MN is the distance between potential electrodes.

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Table 3. Sapotal 2 resistivity measurements. C1 and C2 are positions of current electrodes and P1 and P2 are potential electrodes relative to the start of the profile. AB/2 is half of the distance between current electrodes and MN is the distance between potential electrodes.

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Table 6. Quebro 1 resistivity measurements. C1 and C2 are positions of current electrodes and P1 and P2 are potential electrodes relative to the start of the profile. AB/2 is half of the distance between current electrodes and MN is the distance between potential electrodes.
### Table 4.
Sapota 3 resistivity measurements. C1 and C2 are positions of current electrodes and P1 and P2 are potential electrodes relative to the start of the profile. AB/2 is half of the distance between current electrodes and MN is the distance between potential electrodes.

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### Table 5.
Malena 1 resistivity measurements. C1 and C2 are positions of current electrodes and P1 and P2 are potential electrodes relative to the start of the profile. AB/2 is half of the distance between current electrodes and MN is the distance between potential electrodes.

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5. Discussion

Three locations near the Azuero fault were characterized with the help of Google Earth imagery inspection, cartography and resistivity measurements. Before consider the results obtained at each location, general features of the data acquisition configuration and processing need to be reviewed.

The first consideration is the relief and tilting of the deposits and why I did not take that into account. Because the current flow is concentrated in valleys and dispersed in hills, the equipotential surfaces are distorted producing anomalously low resistivity on hills and high resistivity on valleys (Holocombe and Jirack, 1984). Hence, the terrain effect must be added to the resistivity models. Favorably, this effect is insignificant for slopes of less than 10° (Telford et al., 1990) and the deposits here studied present slopes of 5° maximum.

Second, the ruptures were placed in areas with the lowest resistivity, assuming that fresh water increased its ion content as a result of weathering. In stratigraphic columns a high degree of weathering is recorded, on average, nearly half of the rock is decomposed to soil. This is due to the wet and warm climate allowing ions dissolving in meteoric water.

Also, all terraces where resistivity data was acquired are mapped as alluvial deposits, thus a resistivity of less than 80 Ωm is associated with clays and a resistivity over 100 Ωm is correlated with nearly homogeneous (in composition) and clastic sediments (Fig. 2) deposited by a river. Basaltic clasts comprise most of the gravel lithology, thus gravel is thought to have a higher resistivity than the mud.

Furthermore, parameters in RES2DINV software were adjusted to be more sensitive to vertical narrow structures. For this reason, vertical differences in lithology (horizontal beds) and the groundwater table are difficult to locate.

Additionally, according to Rockwell et al. (2010) neotectonic activity of ASFZ is a strike-slip left-lateral movement, which differs from the strike-slip right-lateral movement recorded in microstructures analyzed by Pérez-Ángel (2015). Thus, Azuero fault may have changed from right-lateral strike-slip to left-lateral strike-slip at some time.

Finally, the assumptions made by Muñoz (1988, 1989, 1990) in which the probability that an earthquake of MM = 7 or more is less than 0.2 present some problems. The first is that most of the earthquakes used to make probabilistic predictions, especially the one in the Azuero province, were before the instrumental era (1505-1992) and their exact locations and magnitudes are unknown. As the average time spacing between events of great magnitude may be hundreds of years, it is difficult to establish the recurrence interval using modern seismicity catalogs.

Second, the Azuero province is located in a complex tectonic area, thus assuming that it is isolated (the tectonic activity around the fault does not affect it neither spatially neither temporally) is quite inconvenient when making the calculations. Muñoz (1988, 1989, 1990) does not take into account that real fault systems involve not just single faults but a wide deformation zone. For example, other faults create complications in the strain field to which the main structure is subjected; movements along the fault zone will tend to increase the stress on adjacent segments of the principal fault and make them more likely to
fail. Also, the faults are accumulating deformation as the time passes, thus base the predictions only in statistics of past events records and not consider that the AF may be getting loaded can result in an unsuitable forecasting.

5.1 Malena

The low resistivity block (resistivity values between 25.6 and 39.9 Ωm) recorded at the resistivity profile 1 is interpreted to have been part of a flood plain. The small range of the resistivity and its low values are due to the rainy weather the couple days before the data acquirement. The water infiltration created a low resistivity block where the differentiation of ruptures becomes difficult.

The pressure ridge inferred at this location, far from the main lineament of the AF could prove that the zone affected by the fault is wide. This structure is approximately 3 km south of the fault which differs in 1 km from Pérez-Ángel (2015) results where a fault zone of 2 km is proposed. However, the location of the pressure ridge is not certain and ambivalence is still present in this conclusion.

5.2 Sapotal

Resistivity lines 2 and 3 present a lower apparent resistivity (42.1 and 97.8 Ωm and 31.4 and 78.0 Ωm, respectively) than line 1 (1.40 and 184 Ωm) due to the rainy weather when taking measurements at these two lines. However, the climate remained dry the days prior to the measurements at Line 1. Dry weather led to low water saturation and consequently to less homogeneous alluvial deposits (very conductive due to the water content) where infiltration of fluids through ruptures (resistivity lows) is more evident.

In resistivity line 1, between 24.5 and 25 m, it can be seen a low resistivity zone, interpreted here as a rupture, of 3.23 – 4.99 m in length. This rupture can be observed in muddy sediments, where resistivity profiles show resistivities of less than 30 Ωm.

Resistivity profile 2 and 3 are thought to be in the ancient flood plain due to the homogeneity of the profile which displays resistivities below 75 Ωm and 80 Ωm respectively. In the resistivity line 1, the right part is inferred to correspond to the flood plain (resistivity values between 45.7 and 11.3 Ωm) and the left part to the channel of an ancient tributary: resistivity values greater than 91.6 Ωm meaning that the sediments are gravel.

The landscape at Sapotal presents two crests with steep slopes and vegetation indicating ancient tributaries. As the terraces are parallel and were differentiated based on its slope, one of these tributaries are thought to be an erosional agent at one side of the crest and a depositional agent at the plain near the crest. “Young” and “old” descriptions are used to differentiate the steeper and the flatter terraces, respectively, that might be produced simultaneously. Figure 30 shows the configuration that could lead to the deposition of both terraces at Sapotal.
Figure 30. Diagram showing the geomorphic feature which could produce terraces 1 (steeper) and 2 (flatter) at Sapotal.

5.3 Quebro

Low resistivity zones located at approximately 2.5 m and 15.5 m of the resistivity profile 1 are interpreted as ruptures. These ruptures are inferred to be in muddy sediments where the highest resistivity is approximately 81 $\Omega$ m. Inside beds of gravel (6 – 11.5 m), ruptures cannot be recognized because the interconnected spaces between clasts allow infiltration of fluids making blocks of gravel homogeneous in resistivity even if they present ruptures. Quebro 1 profile is interpreted as a branch of a river that deposited gravel (high resistivity at the riverbed) and mud at the flood plain (low resistivity to the sides of the river bed) which dried up.

The recent alluvial deposit inspected by Revelo (2015) with GPR turned out to present ruptures at Quebro. Ruptures are placed in Q1 profile (N08°E from south to north) where the reflectors show discontinuities; at 144 m and 222 m (Fig. 15). Quebro 1 resistivity survey intersects Q1 at 140 m (Fig. 32) and shows a rupture at this point (Fig. 29). Taking into account accuracy error of Garmin eTrex GPS of less than three meters for each taken point (start and end of GPR transect and start and end of resistivity transect) the resistivity profile of Quebro shows the same rupture inferred in Q1 GPR profile by Revelo (2015). Due to the match of the vertical discontinuity observed in the GPR survey and the oblique inferred rupture in the resistivity model, the strike of the rupture at surface should be approximately perpendicular to the GPR transect and more parallel to the resistivity profile (~98°) nearly parallel to the main strike of the Azuero fault (120°). This rupture is an R counterclockwise structure shear consistent with the Riedel shear zone of the AF found by Avellaneda (2016).

One of the ruptures at Quebro reaches a depth of at least 4.5 m indicating that neotectonic activity has affected both young and old deposits and thus the adjustment that generated the younger deposit precedes the latest activity.
Terraces at Quebro were differentiated based on their slope and extension (Fig. 31). These observations, complemented with the analysis of Rockwell et al. (2010a), led to one of the possible explanations of the generation of the terraces. Figure 33 shows the three events which could create terraces at this location.
Figure 33.1 shows the original shape of the Quebro River, before the fault affected it. Figure 33.2 shows the terrace adjustment of the oldest terrace after the fault displacement. This event also caused the river course to change and abandon its old channel to start the first valley fill event, depositing sediments of terrace 2. Finally, terrace 3 was created after a climatic event in which Quebro River changed its river course.

Figure 33. Diagram showing the complex tectonic response that generated the oldest terrace T1 (undifferentiated) and T2 and the climatic event which generated T3 at Quebro.

Twelve kilometers southeast of Quebro, a pressure ridge is inferred meaning that the fault could present more than one trace at this location. This inferred pressure ridge is large (approximately 12 km long and 3 km wide) and it is also bent at each end. According to the seismicity map of Panama (Fig. 9), few ruptures of
great magnitude (more than Mb = 7) have taken place, so if the fault has had that behavior in which great events are implausible, the geomorphology present at the fault zone may be product of long time events.

6. Conclusions

- Recent deposits near Azuero fault are composed by highly weathered alluvial rocks.
- At Sapotal and Quebro, resistivity profiles of the recent alluvial deposits show elongated zones of low resistivity, associated to ions in solution due to water infiltration. As the water infiltration is possible along weaknesses, recent alluvial deposits must be faulted.
- The recent deposit at Quebro presents a structural discontinuity striking ~98°, which represent the orientation of a counterclockwise Riedel structure.
- Ruptures in recent deposits at Sapotal and Quebro could represent neotectonic activity of the Azuero Soná fault.
- Recent deposits at Sapotal and Quebro were classified by their relative age based on their slope, elevation and extension. The resistivity profile of Quebro shows that neotectonic activity has affected both young and old deposits, thus, the deposition of the young deposit precedes the neotectonic activity.
- Terraces at Sapotal are thought to be created by one process: a tributary eroded part of the steep slope of a crest and deposited sediments at the same time at the plain near the crest.
- Terraces at Quebro are thought to be produced by first a tectonic event (rupture of the fault) which led to the oldest terrace adjustment and a change in the river course of Quebro River, which, at the same time, deposited sediments of terrace 2. Finally, a climatic event that caused the river course to change again deposited sediments of terrace 3.
- The Azuero-Soná fault is an active strike-slip structure showing geomorphological features such as deflected streams and pressure ridges.
- Comparing the directions of the fold axes in antique rocks, microstructural analysis performed by Pérez-Ángel (2014) and the geomorphological analysis made by Rockwell (2010), the direction of movement of the Azuero-Soná fault shifted from dextral to left lateral.

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References


