Structural evolution of the La Trocha fault zone: Oblique collision and strike-slip basins in the Cuban Orogen

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[1] The La Trocha fault zone acted as a major left-lateral transfer zone and is bounded by the La Trocha (LTF), Zaza-Tuinicú (ZTF), Cristales (CTF) and Taguasco (TGF) faults. These faults were consistent with the clockwise rotation of convergence and shortening in central Cuba. From the Paleocene to the Early Eocene (65–48 Ma), a SSW-NNE shortening produced transtension in the LTF and transpression in the ZTF. Subsequently, during the Middle Eocene (48–37 Ma), shortening shifted to a SW-NE direction, resulting in the normal component of the LTF and transpression in the ZTF and CTF. Since the Late Eocene (37 Ma), central Cuba has been welded to the North American Plate. The post-welding deformation gave rise to transtension of the LTF and TGF. This deformation is consistent with a WSW-ENE shortening and reflects activity in the transform boundary of the Cayman Trough. Both the normal and thrust displacements of these previous faults are corroborated by structural data whereas left-lateral displacement is deduced from the concordance between oblique collision and structural features. Plate-kinematics and the structural evolution of the La Trocha fault zone indicate that the related Central Basin is a strike-slip polygenetic basin and that the formation of this system (i.e., fault zone – strike-slip basin) was a consequence of the Paleogene oblique collision between the Caribbean Volcanic Arc and the Bahamas Borderland (North American plate).

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1. Introduction

[2] Despite the long controversy regarding the origin and evolution of the Caribbean Plate (cf. intraAmerican models by *Ball et al.* [1969], *Donnelly* [1985], *Meschede and Frisch* [1998] and *James* [2006, 2009a, 2009b] and Pacific-derived models by *Wilson* [1966], *Pindell* [1985, 1994], *Pindell et al.* [1988, 2005, 2006] and *Pindell and Kennan* [2009]), the origin in situ of the oceanic strike-slip basins in the NW-Caribbean —i.e., the western Yucatan Basin and Cayman Trough— is generally accepted (Figure 1a). The coeval development of these strike-slip basins with the progressive collision between the Caribbean and North American plates was put forward by *Mann et al.* [1995] and *Mann* [1997]. These authors also propose a model for oblique collision, strike-slip faulting, and the cessation of strike-slip faulting during eastward escape of the Caribbean Plate between the North and South American plates.

[3] In Cuba, the convergence between the Caribbean and North American plates evolved from subduction-accretion in the Late Cretaceous to accretion-collision in the Paleogene, and ended in welding of the resulting orogenic belt —i.e., the Cuban Orogen— in the North American Plate. During this evolution, a rotation of the convergence direction occurred, resulting in an increase in obliquity of the collision [*Gordon et al.*, 1997; *Rojas-Agramonte et al.*, 2005; *Cruz-Orosa et al.*, 2012]. The NW-SE regional trend and major structural features of the Cuban Orogen are in keeping with this evolution, but the coeval formation of a SW-NE to WSW-ENE striking —i.e., transversal to the orogenic belt— left-lateral fault system is a distinctive feature of this orogen. This fault system embraced, from the western Hondo fault to the eastern Oriente transform fault, the Pinar-Varadero, La Trocha and Guacanayabo-Nipe fault zones inside the orogen (Figure 1b). Paleogene activity of these major structures was intrinsically related to the formation and

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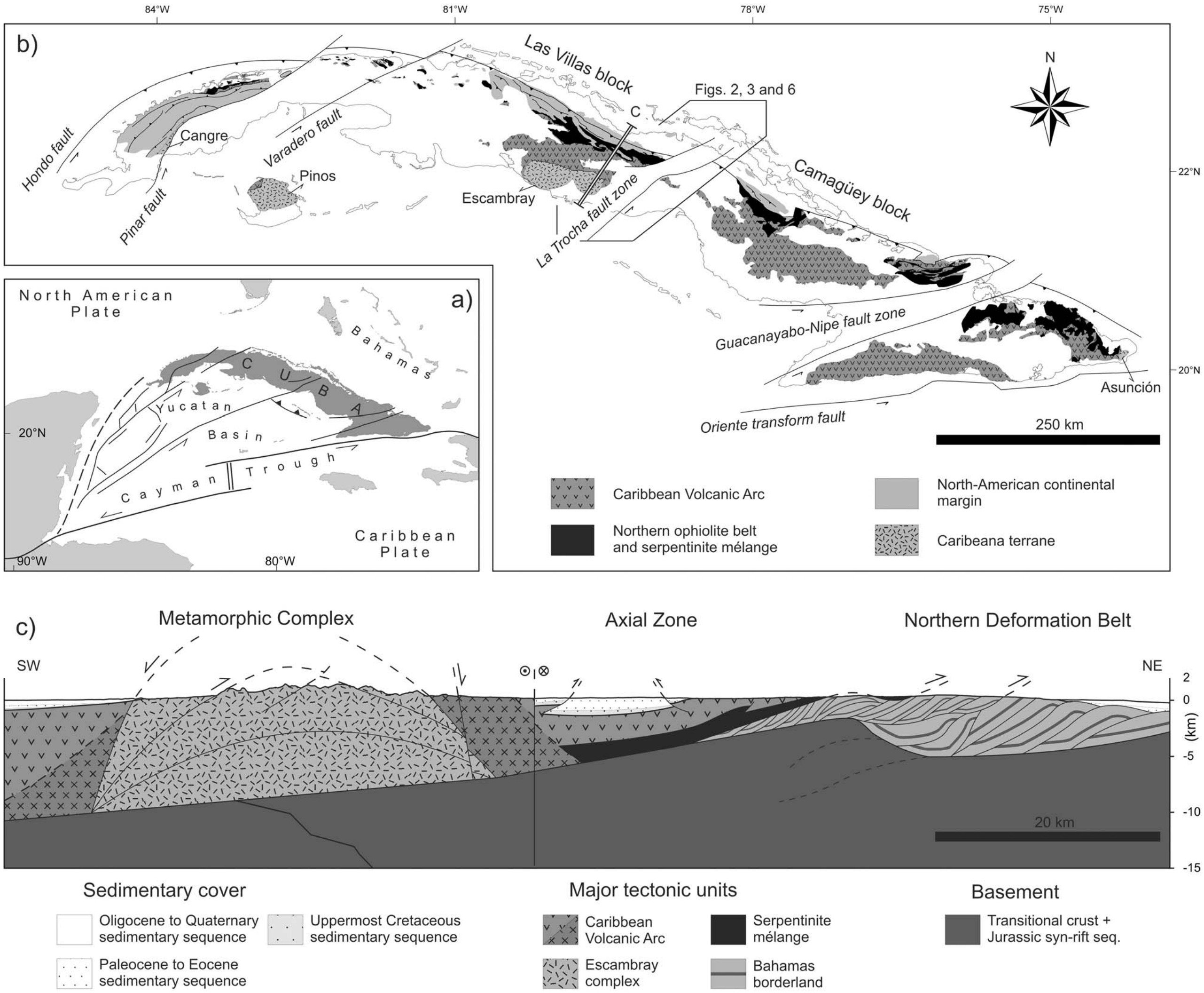

Figure 1. (a) Location of Cuba within the regional framework, compiled from *Rosencrantz* [1990] and *Pindell et al.* [2005]. (b) Geological map of the Cuban Orogen showing the major tectonic units and structures, simplified from *Pushcharovsky* [1988]. (c) Regional transect through the Las Villas block showing structural domains, modified from *Cruz-Orosa et al.* [2012].

evolution of the Yucatan Basin and Cayman Trough [*Rosencrantz et al.*, 1988; *Rosencrantz*, 1990, 1996; *Mann et al.*, 1995; *Leroy et al.*, 2000]. The origin of these structures, however, remains unresolved. It has been suggested that they have been inherited from former faults that extended the volcanic arc. However, available structural data suggest that these structures were consistent with the Paleogene shortening.

[4] Both surface and subsurface data support the structural arrangement of the La Trocha fault zone. The surface geological data show a major structure that acted as a transfer fault zone in the central Cuban orogenic belt [*Linares et al.*, 1985; *Pushcharovsky*, 1988; *García-Delgado et al.*, 1998], whereas the subsurface data record the existence of a sedimentary basin —the Central Basin— linked to this fault zone. Syntectonic sedimentary sequences associated with transtensional faults were deposited in this basin during the Paleogene [*Cruz-Orosa et al.*, 2012]. In addition, regional geophysical surveys record anomalies attributed to the La Trocha fault zone. In particular, the gravity field highlights a SW-NE striking major structure that crosses the orogen [*Sazhina*, 1969; *Ipatenko and Sazhina*, 1971; *Cuevas et al.*, 2001, 2003].

[5] In the present paper, we continue the study outlined by *Cruz-Orosa et al.* [2012]. These authors had synthesized some earlier ideas and had provided new criteria for structural reconstruction of the Cuban Orogen based on a tectonostratigraphic analysis of the central Cuban synorogenic basins. By contrast, in the paper at hand, a detailed structural model and evolution of the La Trocha fault zone is proposed. The present study is supported by a 2D-gravity inversion modeling that was constrained by the available structural data, including surface data, some seismic sections and several boreholes. This modeling will allow us to define some major features of this macrostructure such as its geometry, style of deformation, and structural evolution. Some

elements are also discussed to better understand the tectonic context of the formation of this fault zone and linked strike-slip basins in the Cuban Orogen.

2. Geological Framework

2.1. Regional Setting

[6] The Cuban geology summarizes the tectonic evolution of the northwestern Caribbean during the Late Cretaceous to the Paleogene, when subduction and collision processes involving the Caribbean and North American plates took place [*Rojas-Agramonte et al.*, 2006; *García-Casco et al.*, 2008; *Saura et al.*, 2008; *van Hinsbergen et al.*, 2009; *Cruz-Orosa et al.*, 2012]. During this time span, Cuba was part of a microplate, which was isolated from the neighboring plates and was bounded by the Proto-Yucatan Basin to the south and by an active frontal-oblique collision zone to the north (Figure 1). Extension in the intraarc Yucatan Basin produced the split of the northwestern branch of the Caribbean Volcanic Arc (Cuban sector) and the exhumation of some metamorphic complexes —cf. the Caribeana terrane— in the Cuban Orogen [*Pindell et al.*, 2005; *García-Casco et al.*, 2008; *Stanek et al.*, 2009]. Compression was recorded in a fold-and-thrust belt affecting the North-American passive continental margin in the northern structural domain of the orogen [*Cruz-Orosa et al.*, 2012]. Subsequently, the origin and evolution of the Cayman Trough led to the cessation of extension in the Yucatan Basin and to the formation of the current transform boundary between the Caribbean and North American plates [*Holcombe et al.*, 1973; *Rosencrantz et al.*, 1988; *Mann et al.*, 1995, 2002; *Leroy et al.*, 2000] (Figure 1a). The post-Eocene deformation mainly occurred in major fault zones and to the foreland [*Gordon et al.*, 1997; *Masaferro et al.*, 1999, 2002; *Rojas-Agramonte et al.*, 2005; *Cruz-Orosa et al.*, 2012].

[7] The major tectonic units involved in the Cuban Orogen are shown in Figure 1b. The Caribbean Volcanic Arc developed as a consequence of the subduction of the Proto-Caribbean oceanic lithosphere —i.e., the North American Plate— beneath the Pacific oceanic lithosphere —i.e., the Caribbean Plate— [*Pindell and Dewey*, 1982; *Pindell et al.*, 2005, 2006]. Paleomagnetic data support a gradual northeastward motion and anticlockwise rotation during the evolution of the volcanic arc [*Renne et al.*, 1991; *Chauvin et al.*, 1994; *Tait et al.*, 2009]. Volcanic activity lasted until the Early Campanian in western and central Cuba whereas it lasted until the Eocene times in eastern Cuba [*Rojas-Agramonte et al.*, 2004, 2006, 2008]. The Caribbean Volcanic Arc is omnipresent in the geology of Cuba and is represented mainly by volcanic, volcano-sedimentary and plutonic rocks [*Iturralde-Vinent*, 1996a; *Furrazola-Bermúdez and Núñez-Cambra*, 1997; *Proenza et al.*, 2006; *Stanek et al.*, 2009]. The deepest exposed section of the volcanic arc and its oceanic basement is represented by the amphibolitic Mabujina complex [*Somin and Millán*, 1981; *Millán*, 1996]. However, *Blein et al.* [2003] suggest that the Mabujina complex forms part of a different and older volcanic arc (Figure 2). During the Late Campanian, volcanic activity ceased because of the subduction and accretion of the Caribeana terrane. According to *García-Casco et al.* [2008], this terrane was a portion of the Proto-Caribbean domain and displayed features similar to those of the North-American continental margin. Exhumation of the Caribeanan rocks started during the Maastrichtian and resulted in the outcrop of some metamorphic complexes. The incipient orogenic belt continued to collide with the continental margin of the North American Plate —cf. the Yucatan and Bahamas borderlands— until the Eocene, when the Cuban Orogen was transferred to the North American Plate. The suture zone is marked by an extensive ophiolite belt and serpentinite mélange that crops out in the northern part of the Cuban Orogen [*Iturralde-Vinent*, 1996b; *Cobiella-Reguera*, 2005, 2009; *Lewis et al.*, 2006; *García-Casco et al.*, 2006] (Figure 1b).

[8] The structural transect in Figure 1c shows that the Caribbean Volcanic Arc and serpentinite mélange are allochthonous on the North-American continental margin —i.e., the Bahamas borderland— in the central Cuban orogenic belt. This borderland is very deformed in a thin-skinned imbricated thrust system forming the Northern Deformation Belt. The Bahamas series have been described by several authors, including *Meyerhoff and Hatten* [1968, 1974], *Pszczólkowski* [1986, 1999] and *Pszczólkowski and Myczynski* [2003, 2010]. The Caribbean Volcanic Arc and serpentinite mélange occupy the Axial Zone of the orogen, forming a partially imbricated synclinorium, whereas the Escambray complex — cf. the Caribeana terrane— is a dome below the volcanic arc suite. Data from *Renne et al.* [1989], *Otero et al.* [1998] and *Moreno Toiran* [2003] suggest that the basement of these major tectonic units is an extended, Neoproterozoic transitional crust.

2.2. La Trocha Fault Zone and Central Basin

[9] The La Trocha fault zone is collinear with the trans-basin fault, which separates the western and eastern domains of the Yucatan Basin [cf. *Rosencrantz*, 1990] (Figure 1a). This author also suggests that the trans-basin fault was a left-lateral transcurrent fault and that the amount of its offset was less than 50 km. The age of the trans-basin fault is not clear.

[10] The main stage of deformation in the La Trocha fault zone occurred during the Paleogene, when some areas subsided and syntectonic sedimentary sequences accumulated in marine environments. All these depositional areas, in conjunct, are denominated the Central Basin [*Cruz-Orosa et al.*, 2012] (Figure 2a). The Central Basin was developed on an active substratum that was partially affected by thrust and strike-slip faults. Several tectonic blocks were differentiated as a result of vertical motions inside the fault zone and two main depocenters were developed (Figure 2b). In the southwestern depocenter, sediments exceed 3000 m in the Sancti Spíritus_1 borehole whereas, in the northeastern depocenter, sediment thickness is smaller —around 1000–1500 m. Both depocenters are separated by a structural high in the Jatibonico_78 borehole.

[11] The Cenozoic sedimentary infill of the Central Basin unconformably overlies (U_0 in Figure 2b) the volcanic rocks and the uppermost Cretaceous sedimentary sequence. However, borehole data show that other types of rocks —i.e., ophiolitic and metamorphic rocks, and continental margin series— are also involved in the basin substratum. The volcanic sequences are very common in the substratum, consisting of volcanic, volcano-sedimentary and sedimentary rocks, with subordinate plutonic rocks. In the Jatibonico_78 borehole, this suite exceeds 3000 m in thickness. The uppermost Cretaceous sequence covers the volcanic rocks with angular unconformity. Both sequences are cut by the

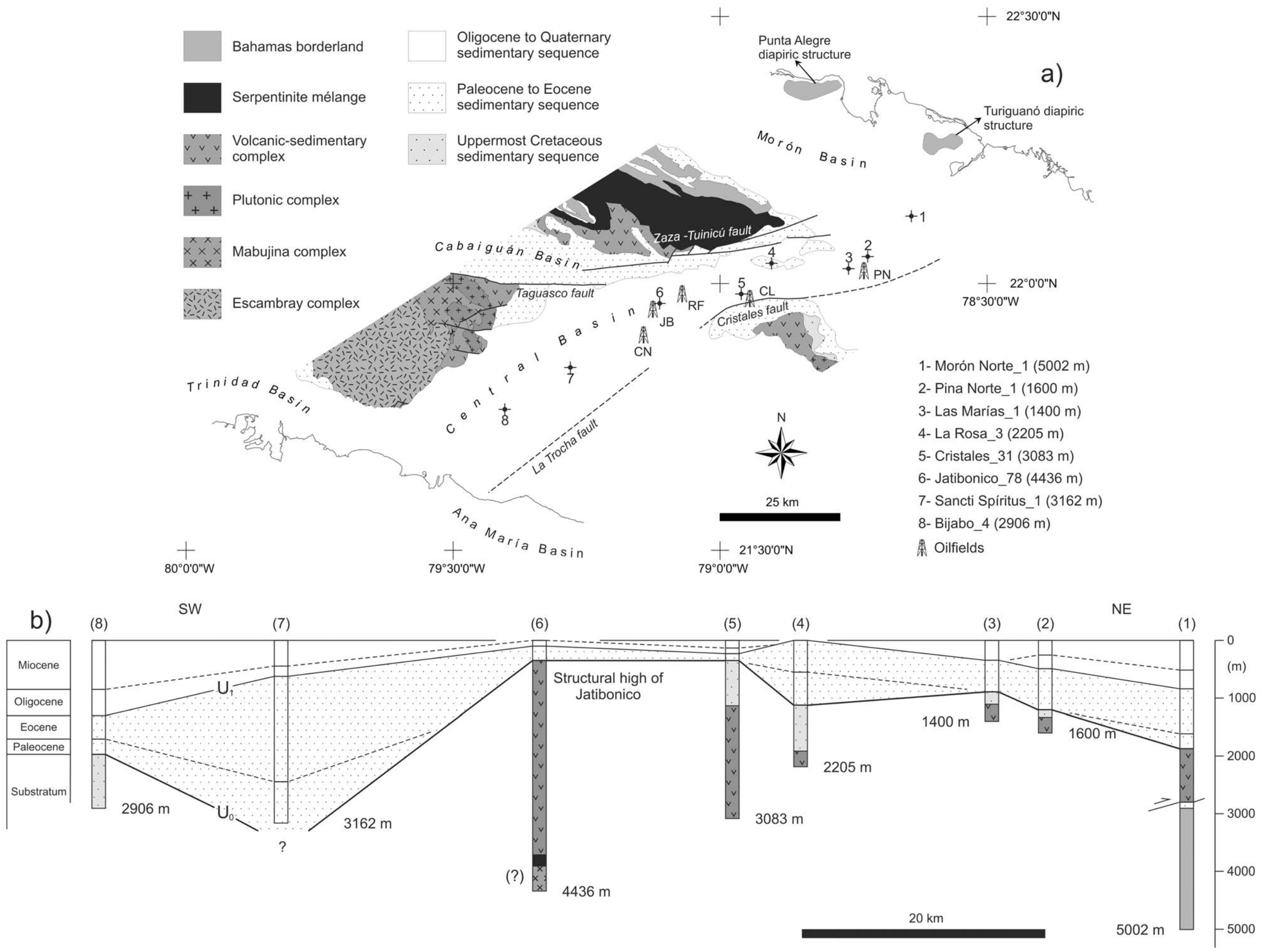

Figure 2. (a) Geological map and (b) longitudinal correlation panel of the La Trocha fault zone. U_0 = basal unconformity, and U_1 = unconformity between the lower (Paleocene to Eocene) and upper (Oligocene to Quaternary) sedimentary sequences. Major tectonic units are compiled from *García-Delgado et al.* [1998]. The oilfields are, from west to east: Catalina (CN), Jatibonico (JB), Reforma (RF), Cristales (CL), and Pina (PN).

major faults of the La Trocha fault zone [*Cruz-Orosa et al.*, 2012]. The uppermost Cretaceous sequence is made up of terrigenous to clastic-carbonate and calcareous rocks and their thicknesses range between 0 and more than 1000 m. Moreover, ophiolitic and metamorphic rocks are scarce in the basin substratum and have only been documented in few wells —e.g. the Jatibonico_78. The Bahamas borderland sequences have been sampled in the Morón Norte_1 borehole below the volcanic suite.

[12] Two main sequences can be differentiated in the sedimentary infill of the Central Basin: a lower sequence, Paleocene to Eocene in age, which is syntectonic with the main regional deformation; and an upper sequence from the Oligocene to the Quaternary. The Paleocene to Eocene sedimentation was eminently terrigenous. It was produced by erosion of the orogen and was deposited in deep-marine environments. The Oligocene to Quaternary sequence is mainly composed of calcareous series of shallow-marine and transitional environments (see descriptions by C. W. Hatten et al. (Geology of central Cuba, eastern Las Villas and western Camagüey provinces, Archivo del Servicio Geológico Nacional, Havana, Cuba, unpublished report, 1958), I. Kantchev (Informe geológico de la provincia Las Villas: Resultados de las investigaciones geológicas a escala 1:250000 durante el período 1969–1975, Archivo del Servicio Geológico Nacional, Havana, Cuba, unpublished report, 1978), and *Cruz-Orosa et al.* [2012]). Both sequences are separated by a regional unconformity (U_1 in Figure 2b). The Paleocene to Eocene sedimentary sequence includes olistostromic and turbiditic series, which grades laterally and upward to carbonate platform and neritic series. Detritic material is polymictic made up of andesite, granitoid, tuff, basalt, chert, sandstone, and limestone clasts. In the carbonate platform and neritic series, the limestones, marls, calcarenites and polymictic sandstones are predominant. The Paleocene to Eocene sedimentary sequence varies considerably in thickness. Its maximum value is in the Sancti Spíritus_1 borehole (over 2500 m), but the most common range is from 100 to 800 m (Figure 2b). The Oligocene to Quaternary sedimentary sequence is made up of limestones, marls, calcarenites and biocalcarenites, with some clastic input around the Escambray Mountains. Thicknesses are more significant toward the SW, exceeding 1300 m in the

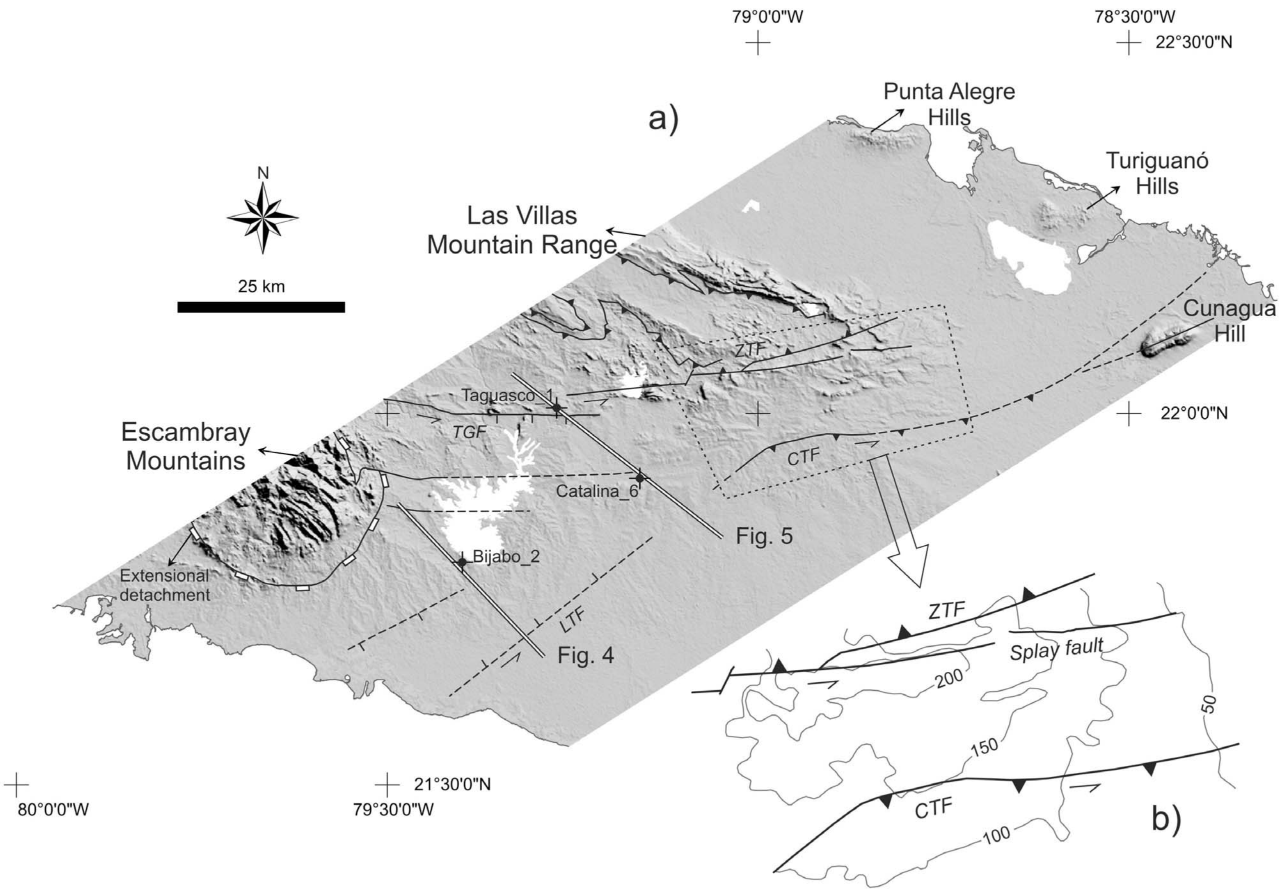

Figure 3. (a) Structural map in shaded relief of the La Trocha fault zone. Major structures are the La Trocha (LTF), Zaza-Tuinicú (ZTF), Cristales (CTF) and Taguasco (TGF) faults. Geometry of major structures was compiled from a broader grid of seismic data (e.g., LTF and TGF) and/or from surface data (e.g., ZTF and CTF). (b) Detail showing an alignment in relief associated with the splay in the Zaza-Tuinicú fault. See also Figure 2 to compare with surface geology.

Bijabo_4 borehole (Figure 2b). In the central and northeastward parts of the basin, the Oligocene to Quaternary sequence is thinner and may even be absent, but it is more significant around the Morón Norte_1 borehole.

3. Structural Modeling

[13] The La Trocha fault zone and Central Basin have been extensively studied as a result of oil exploration. This has given rise to a large number of exploration wells throughout the structure and to some detailed seismic studies and regional gravity surveys. However, boreholes are not sufficient for regional modeling and the quality of the available seismic data is not suitable for prospecting in some areas. Therefore, gravity data become a major tool for integrating available structural constraints into the model.

3.1. Structural Constraints

[14] The La Trocha fault zone behaves like a transtensive transfer fault although some structures result from transpression. This fault zone is bordered by some major faults that behaved differently during deformation. The major faults are the La Trocha (LTF), Zaza-Tuinicú (ZTF), Cristales (CTF) and Taguasco (TGF), despite other minor faults (Figures 2 and 3).

[15] The SW-NE-oriented LTF, which forms the southeastern boundary of the La Trocha fault zone, is the main fault of the system. It is not documented in surface despite being well known from seismic data (Figure 4). In the southwestern part of the Central Basin, the LTF shows a marked normal displacement, at around of 1.5 s of TWT (two-way traveltime). The fault cut and displaced the top of substratum, giving rise to a half-graben that filled with syntectonic sedimentary sequences from the earliest Paleocene to the Eocene. Some activity of this fault may have been retained until the earliest Miocene. Moreover, an antithetic fault developed to the SW, forming geometries that locally resemble a graben. The LTF is attenuated toward the NE (Figures 3 and 5).

[16] The WSW-ENE-oriented ZTF and CTF constitute the main boundaries of the northern La Trocha fault zone. Both faults have a thrust character and form a structure that resembles a compressional triangle zone. The ZTF shows a splay fault. The main fault is marked by surface geology (Figure 2) whereas the splay is prominent in a relief alignment (Figure 3b). The splay fault is younger and has a strike-slip character. According to *Linares et al.* [1985],

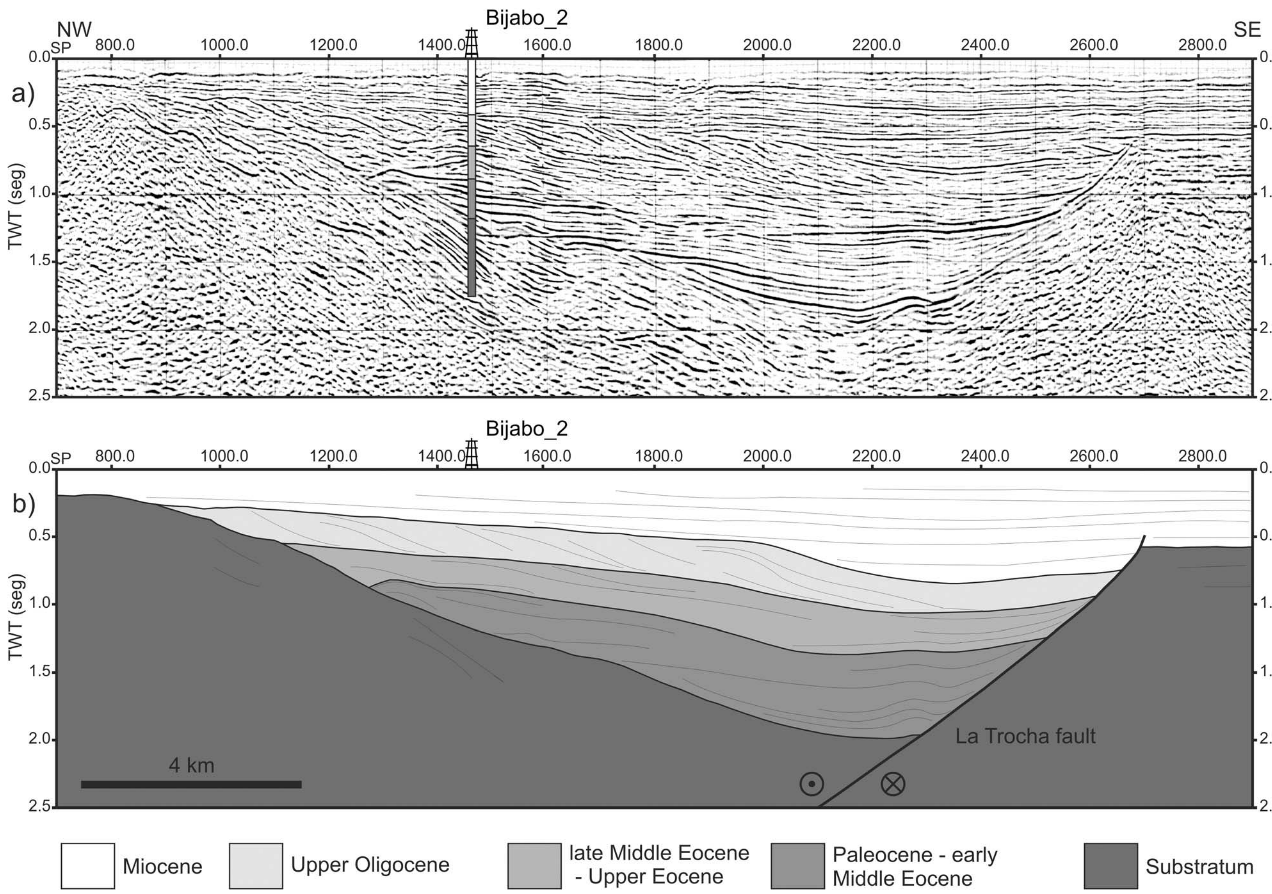

Figure 4. (a) NW-SE seismic section and (b) line-drawing of the southern La Trocha fault zone showing a half-graben associated with the La Trocha fault. Interpretation is based on the Bijabo_2 borehole. The fit of the borehole log in seismic section was supplied by CubaPetróleo. See location in Figure 3.

Pushcharovsky [1988], and *García-Delgado et al.* [1998], the hanging wall of the ZTF is made up of ophiolitic and volcanic rocks. The age of the sedimentary rocks involved in the footwall ranges from the Paleocene to the Eocene. These criteria suggest that the ZTF was active after the Eocene. Meanwhile, the CTF is well documented in the Cristales oilfield that is linked to it (Figures 2 and 3). In this area, the hanging wall contains the Paleocene to Eocene sequence whereas both the Paleocene to Eocene and Oligocene to Quaternary sequences are included in the footwall. This strongly suggests that thrust displacement of the CTF is less than in the ZTF and that the CTF could be younger and was probably active until the earliest Miocene. The local uplift in the Cunagua Hill was probably related to transpression of the CTF (Figure 3).

[17] The boundary between the Cabaiguán and Central basins is marked in surface geology by the W-E-oriented TGF (Figures 2a and 3). However, this boundary is complex as shown in Figure 5. The Paleocene to Eocene sequence is involved both in the hanging and footwall of the TGF normal fault but the deformation pattern is different on both sides of the fault. In the footwall, the seismic image is diffuse around a structural high in the Taguasco_1 borehole and the Upper Eocene layers are probably folded in a compressional setting. By contrast, in the hanging wall the sedimentary record reaches the Miocene with evidence of extensional drag folding. The structural high in Figure 5 is interpreted as an antiformal stack that was subsequently cut by the normal fault. All these criteria suggest that at least two deformation events overlapped at the boundary between the Cabaiguán and Central basins. The compressional structure is younger than the Late Eocene and the TGF normal fault occurred in the Late Oligocene-Early Miocene.

[18] Figure 5 also shows some late strike-slip flower structures that cut the Paleocene to Oligocene sedimentary record. These structures are covered by the Miocene succession and are probably related to a late strike-slip motion in the TGF. Furthermore, the northeastern branch of the Central Basin is very structured and according to E. Milián (Caracterización de las facies colectores y sellos y su distribución areal para los depósitos Cretácico-Paleógenos de la Cuenca Central de Cuba, Archivo de la EPEP-Majagua, Ciego de Ávila, Cuba, unpublished report, 1987), *Peña-Reyna et al.* [2007], and *Cruz-Orosa et al.* [2007] lateral displacements of blocks can exceed 1000 m in a SW-NE direction.

[19] The structural map in Figure 6 represents the basal unconformity (U_0) of the Central Basin. The southern depocenter forms a half-graben related to the LTF and is limited by the Escambray Mountains to the NW and by the TGF to the north (Figures 2, 3 and 4). The northern depocenter is much smaller and not as deep —1486 m in the

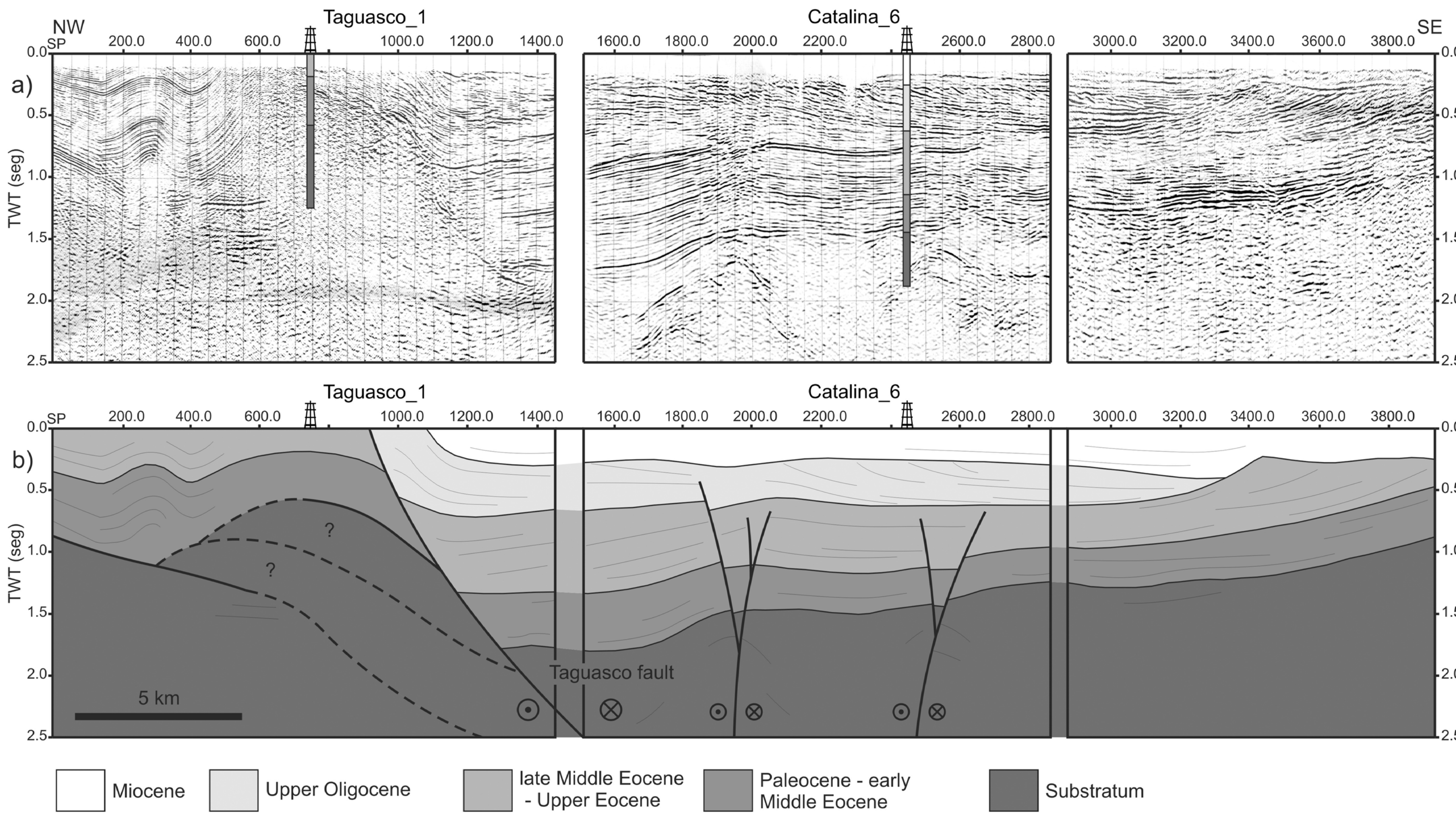

Figure 5. (a) NW-SE seismic section and (b) line-drawing of the central La Trocha fault zone showing a multiphase structure in the boundary between the Cabaiguán and Central basins. Interpretation is based on the Catalina_6 and Taguasco_1 boreholes. The fit of the borehole logs in seismic section was supplied by CubaPetróleo. See location in Figure 3.

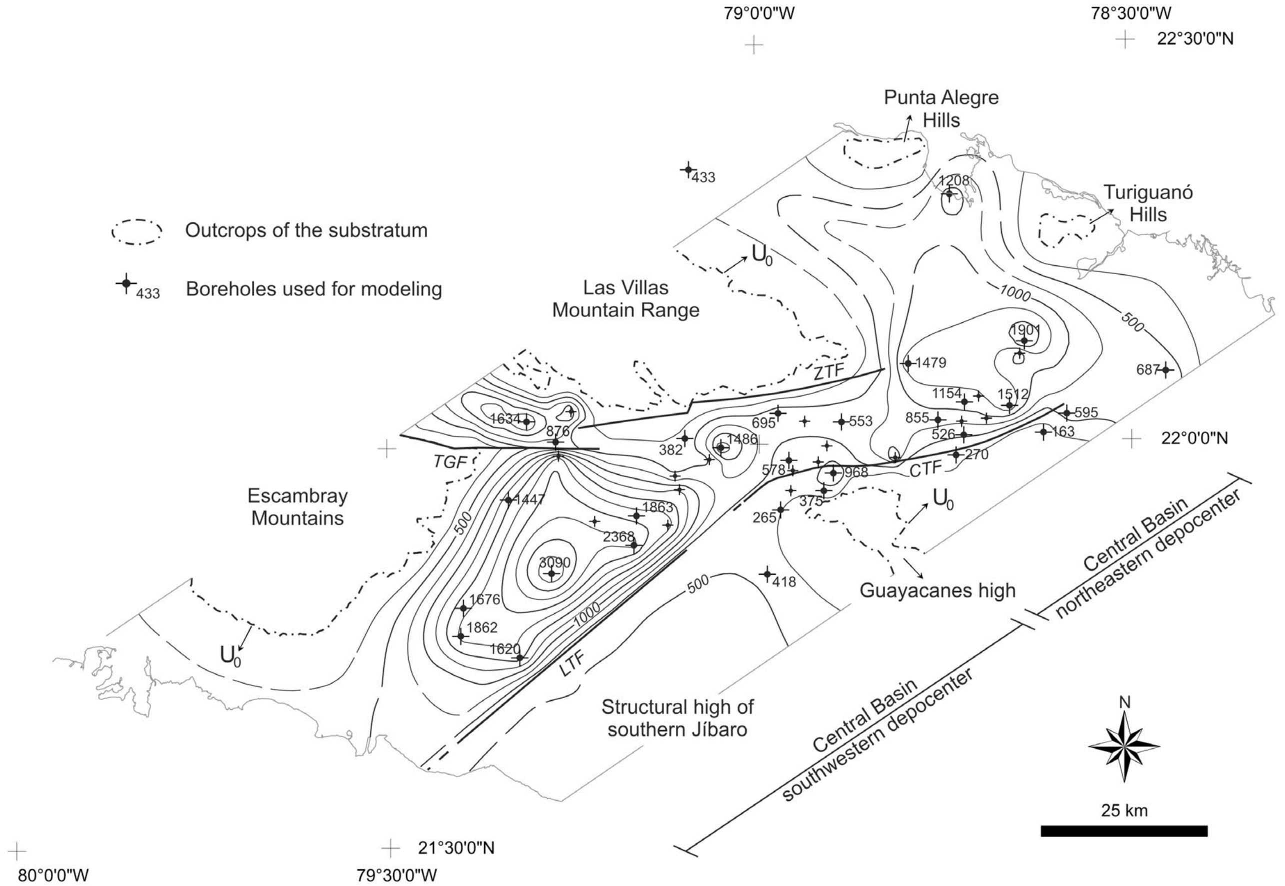

Figure 6. Structural map of the basal discontinuity (U_0) in the Central Basin. Map is constructed from borehole data and constrained by seismic sections and surface data. Contour lines are separated by 250 m. See also Figures 2 and 3 for comparison with surface geology.

Reforma oilfield— as the southern depocenter and is limited by the CTF and ZTF to the SSE and NNW, respectively. This depocenter is connected with the broken foreland Morón Basin, which is located to the NE. The southern and northern depocenters are separated by the Jatibonico structural high, where the basal unconformity is at less than 500 m deep.

3.2. Gravity and Density Data

[20] The regional gravity field in Figure 7a reflects very well the structure of the Cuban Orogen [cf. *Sazhina*, 1969; *Cuevas et al.*, 2001, 2003]. Broadly speaking, it shows a regional SSW trending gradient, but also includes anomalies generated by local structures such as the La Trocha fault zone (Figure 7b). The northern flank of the orogen is characterized by negative anomalies (down to −30 mGal) that are probably attributed to the imbricated system of the Bahamas borderland and to a greater thickness of the transitional crust. By contrast, the gravity field in the southern flank presents positive anomalies, commonly between 0 and 100 mGal but it can exceed 180 mGal in eastern Cuba. These anomalies are linked to the volcanic arc and ophiolitic rocks, which are allochthonous on the margin sequences and which are deformed by some domes made up of metamorphic rocks [*Bush and Shcherbakova*, 1986; *Pardo*, 1996; *García-Casco et al.*, 2008].

[21] The Central Basin has been extensively studied by gravity surveys, e.g., I. Kireev (Informe referente a la exploración gravimétrica de la Cuenca Central, Archivo del Servicio Geológico Nacional, Havana, Cuba, unpublished report, 1963), S. Ipatenko (Informe sobre las investigaciones magnetométricas y gravimétricas en la provincia de Camagüey, Archivo del Servicio Geológico Nacional, Havana, Cuba, unpublished report, 1968), M. Rodríguez and J. L. Prol (Informe sobre el levantamiento gravimétrico detallado del área Mayajigua-Morón, Archivo de la Empresa Nacional de Geofísica, Havana, Cuba, unpublished report, 1980), and M. Rodríguez and R. Domínguez (Informe sobre los resultados del levantamiento gravimétrico en Jatibonico-Pina-Esmeralda, Archivo de la Empresa Nacional de Geofísica, Havana, Cuba, unpublished report, 1993). The two most recent surveys were conducted at local scale with exploratory aims. Modeling was therefore performed on the basis of the data obtained by Ipatenko between 1962 and 1968. These data include a significant amount of primary data and a unified Bouguer anomaly map of the Central Basin and surrounding areas at 1:50000 scale. Primary data in Figure 7c were acquired along the road network with a measurement point every 400 m. A coverage of 1.6 point/km^2 resulted from the ratio between the number of measurements and the surveyed surface. The Bouguer map in Figure 7b was

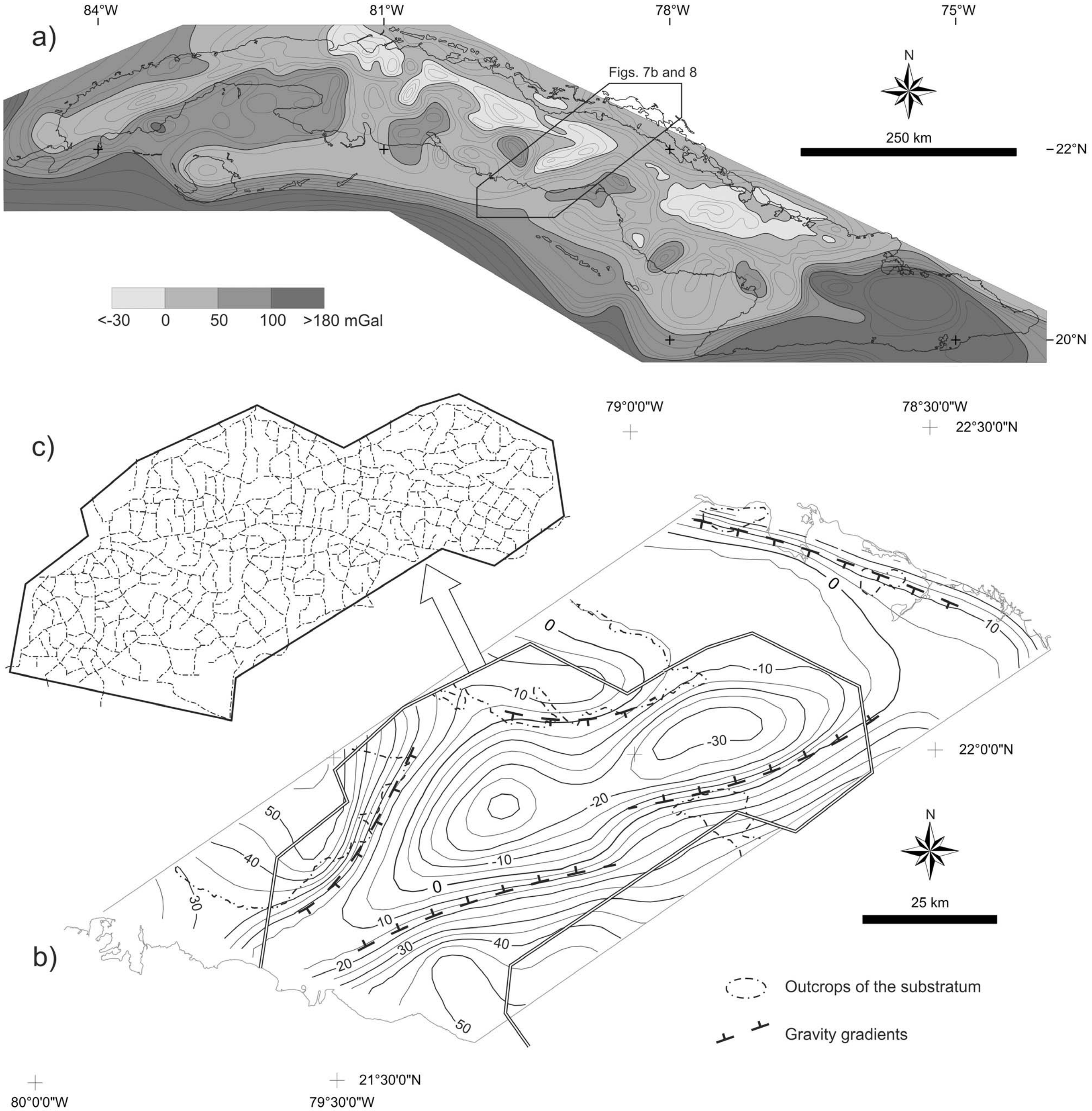

Figure 7. (a) Bouguer anomaly map (σ = 2.3 g/cm^3) of the Cuban Orogen, modified from *Ipatenko and Sazhina* [1971]. (b) Bouguer anomaly map (σ = 2.3 g/cm^3) and (c) location of primary gravity data of the Central Basin and surrounding areas, compiled from Ipatenko (unpublished report, 1968).

constructed from the regularization of these primary data together with data from other regional surveys. The original mean quadratic error of this map was estimated at ±0.34 mGal, but it increased to ±0.8 mGal as a result of the digitalization process.

[22] The Bouguer map in the Central Basin is characterized by an intense negative anomaly striking SW-NE (Figure 7b). It consists of two gravity minimums (down to −30 mGal) that are separated by the structural high of Jatibonico (Figure 2b). At first sight, it seems that the entire anomaly is generated by the same sources. However, the subsurface data confirmed that the southwestern branch is partially induced by more than 3000 m of sedimentary infill, whereas the substratum is cut at depths between 500 and 1500 m in the northeastern branch. *Gómez-García and Prol* [2001] suggest that the substratum includes sedimentary rocks —probably belonging to the Bahamas borderland— under the volcanic arc rocks to the NE. This hypothesis would offset the gravity intensity in both areas and is structurally possible given that the volcanic and ophiolitic rocks are allochthonous on the margin sequences as is in the surface geology and in the Morón Norte_1 borehole (Figures 1c and 2).

Table 1. Density of Rocks in the Studied Area; Major Sequences and Rock Types are Differentiated[a]

	Sequences and Main Rock Types	$n(1)$	Mean(1)	$n(2)$	Mean(2)
Sedimentary infill	*Oligocene to Quaternary sedimentary sequence*	*520*	*2.30*		
	Claystones and mudstones	211	2.050	-	-
	Marls	75	2.103	-	-
	Marly limestones	57	2.350	-	-
	Limestones	79	2.610	-	-
	Organogenic limestones and marls	33	2.303	-	-
	Calcarenites	65	2.405	-	-
	Paleocene to Eocene sedimentary sequence	*404*	*2.35*		
	Shales and siltstones	17	2.225	-	-
	Sandstones (undifferentiated)	65	2.306	-	-
	Polymictic sandstones	121	2.317	-	-
	Tuffaceous sandstones	117	2.350	-	-
	Conglomerates and breccias (undifferentiated)	31	2.500	-	-
	Polymictic conglomerates	13	2.362	-	-
	Tuffaceous conglomerates	40	2.392	-	-
Substratum	*Volcanic arc*	*96*	*2.66*		
	Pyroclastic and epiclastic	54	2.550	-	-
	Volcanic and sub-volcanic	30	2.600	-	-
	Plutonic	12	2.846	-	-
	Ophiolitic	*194*	*2.72*	*55*	*2.82*
	Basalts	3	2.700	7	2.870
	Gabbros	35	2.950	30	2.878
	Serpentinized peridotites	156	2.500	18	2.706
	Sedimentary (Bahamas borderland)	*186*	*2.53*	*16*	*2.60*
	Marls	37	2.220	-	-
	Limestones	25	2.615	16	2.600
	Dolostones	124	2.766	-	-
	Metamorphic			*13*	*2.85*
	Schists	-	-	7	2.810
	Amphibolites	-	-	2	3.080
	Marbles	-	-	4	2.670

[a]Density data are from two sources: 1) from unpublished technical reports (1968 and 2001) and/or databases (consulted in 2008) of CUPET; and 2) measurements made for this work. Mean = arithmetic mean of population in g/cm^3, and n = number of tests.

[23] The gravity gradients shown in Figure 7b are ascribed to the zones of change between positive and negative values and mark the limits of the sedimentary basins (see also Figures 2, 3 and 6). The main gradients are located to the SE as a result of the density contrast generated by the LTF and CTF. The NW and western gradients are attributed to the ZTF and to the density differences between the metamorphic rocks of the Escambray complex and the sedimentary infill of the Central Basin, respectively. Moreover, according to the qualitative interpretation of gravity data from *Peña-Reyna et al.* [2007], some SW-NE and NW-SE alignments occur in the basin and could constitute tectonic or lithologic contacts.

[24] Density data in Table 1 come from two sources. Most data were taken from unpublished technical reports (1968 and 2001) and/or databases (consulted in 2008) of CubaPetróleo (CUPET) and come from surface and borehole samples. The rest is our data, which were acquired from surface samples and were used as complementary data. Densities were obtained from the measurement of mass and volume. A total of 1484 tests were considered.

[25] On the substratum, density varies depending on the composition and rock types (Table 1). The volcanic arc sequence is widespread with the result that it has a major impact on the gravity field. Higher density values correspond to plutonic rocks —mainly diorites and granodiorites— with a mean of 2.846 g/cm^3. In pyroclastic and epiclastic rocks —mainly agglomerates and tuffs— density is 2.550 g/cm^3 and in the intermediate volcanic and sub-volcanic rocks it is 2.600 g/cm^3. The mean density of the volcanic arc sequence —including plutonic rocks— is 2.66 g/cm^3. This value in the volcanic-sedimentary sequence —excluding plutonic rocks— increases to 2.68 g/cm^3 because of the effect of burial depth (Table 2). Burial depth also affects the densities of the Bahamas sequence, whose mean values increase to 2.70 and 2.75 g/cm^3 in the continental slope/deep water basin and continental platform sequences, respectively. In addition, mean densities of the ophiolitic sequence range from 2.72 to 2.82 g/cm^3 according to the data source under consideration, whereas in metamorphic complexes they depend primarily on the rock type and its metamorphic grade.

[26] Rock density of the sedimentary infill varies with depth although a trend is attributed to the compositional

Table 2. Density Estimated to Adjust Burial Effect in Sedimentary Sequences[a]

Sequences and Stratigraphic Intervals		Density (g/cm^3)
Sedimentary infill	Quaternary	2.25
	Miocene	2.30
	Oligocene	2.45
	Eocene	2.50
	Paleocene	2.60
	Uppermost Cretaceous	2.65
Volcanic-sedimentary sequence		2.68
Bahamas borderland: continental slope and deep water basin		2.70
Bahamas borderland: continental platform		2.75

[a]Burial effect was corrected by density of borehole samples from unpublished technical reports (1968 and 2001) and/or databases (consulted in 2008) of CUPET.

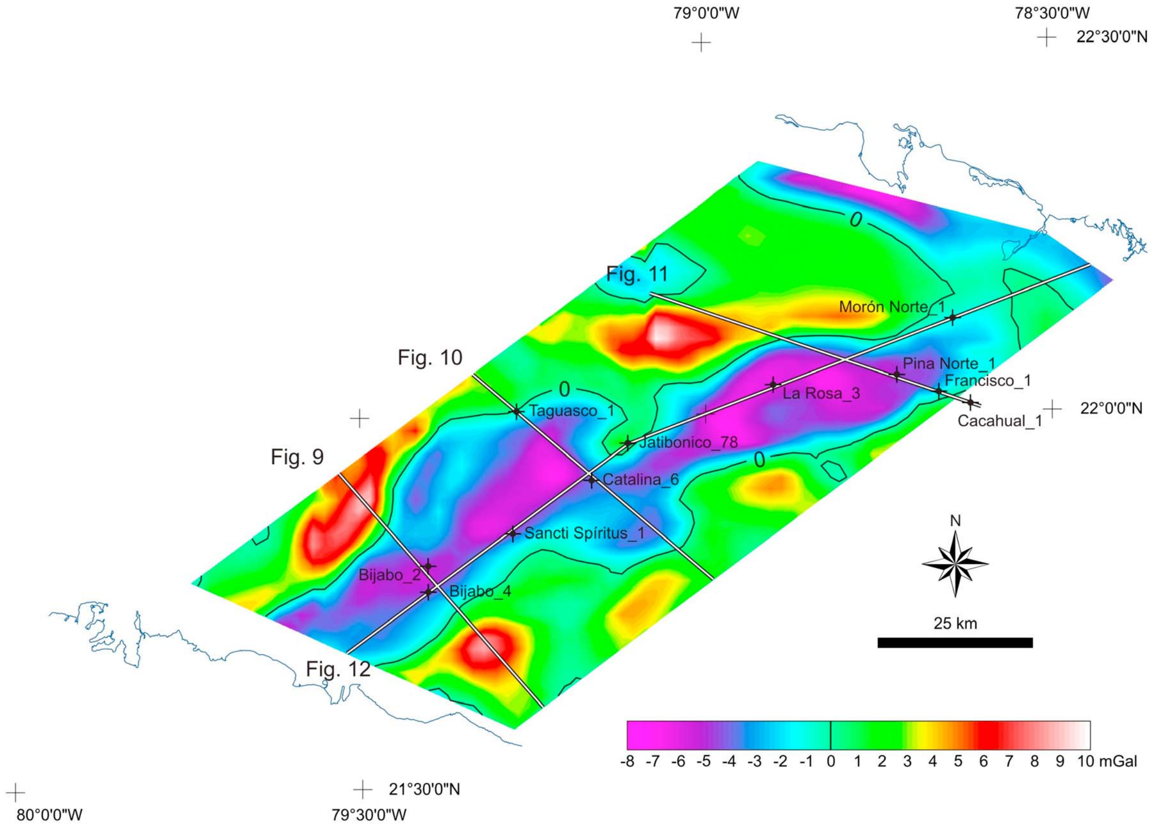

Figure 8. Residual gravity anomaly map of the Central Basin and surrounding areas. Map is based on data from Ipatenko (unpublished report, 1968).

differences between the Paleocene to Eocene and Oligocene to Quaternary sequences. The oldest sequence is eminently terrigenous —with a mixed composition— and its mean density is 2.35 g/cm^3, from 2.500 g/cm^3 in conglomerates and breccias to 2.225 g/cm^3 in shales and siltstones. The youngest sequence is more calcareous —partially argillaceous— and its mean density is 2.30 g/cm^3, from 2.610 g/cm^3 in limestones to 2.050 g/cm^3 in claystones and mudstones (Table 1). The burial depth correction of densities in the stratigraphic succession is shown in Table 2.

3.3. Inversion Gravity Models

[27] Gravity inversion was based on the methods of *Talwani et al.* [1959], *Talwani and Heirtzler* [1964] and other complementary algorithms implemented in GM-SYS by Geosoft Inc. The residual anomaly map in Figure 8 was used as primary gravity data for the inversion process and was selected because it was the best fit to surface geology and the Central Basin limits. This map results from the difference between the Bouguer map shown in Figure 7b and a regional anomaly map that was obtained by the Moving Average method with an isotropic search ellipse at 10000 m. A residual gravity inversion up 5000 m in depth was performed in accordance with this criterion.

[28] The residual component of the gravity field highlights the regional structure, showing a major negative anomaly in a SW-NE direction that is limited by several smaller positive anomalies to the NW and SE. The negative anomaly is produced by the sedimentary infill of the Central Basin whereas the positive anomalies are linked to substratum sources. In addition, at the northern end there is another negative anomaly probably attributed to the Punta Alegre and Turiguanó salt sheet structures (Figures 2 and 3). Figures 9, 10, 11 and 12 show four regional transects obtained by a 2D-gravity inversion. Three of these models were plotted transversely through the La Trocha fault zone and one longitudinally to this macrostructure (see location in Figure 8). All the models were constrained by the available structural data of surface geology, drilling and seismic sections, and were extended 5 km in the $-X$ and $+X$ directions to eliminate edge effects.

[29] Figure 9 shows a NW-SE transect of the southern La Trocha fault zone, from the Escambray Mountains to the south of Jíbaro through the Central Basin (Figures 6 and 8). The observed gravity curve varies from -5.5 to 8.7 mGal and shows a fairly symmetrical geometry in profile. It may be interpreted as having resulted from a central low-density zone —occupied by the main depocenter of the Central Basin— between two structural highs of substratum to the NW and SE, respectively. The basin geometry is compiled from seismic and borehole data (Figure 4) whereas the substratum structure has been inferred from fitting the residual gravity data. In this transect, the Central Basin shows a half-graben geometry related to the La Trocha fault. The LTF presents a normal component with growth strata that exceed 1200 m in thickness. This fault cuts the uppermost Cretaceous sedimentary sequence and the volcanic arc rocks. The Escambray complex, which is representative of the southern

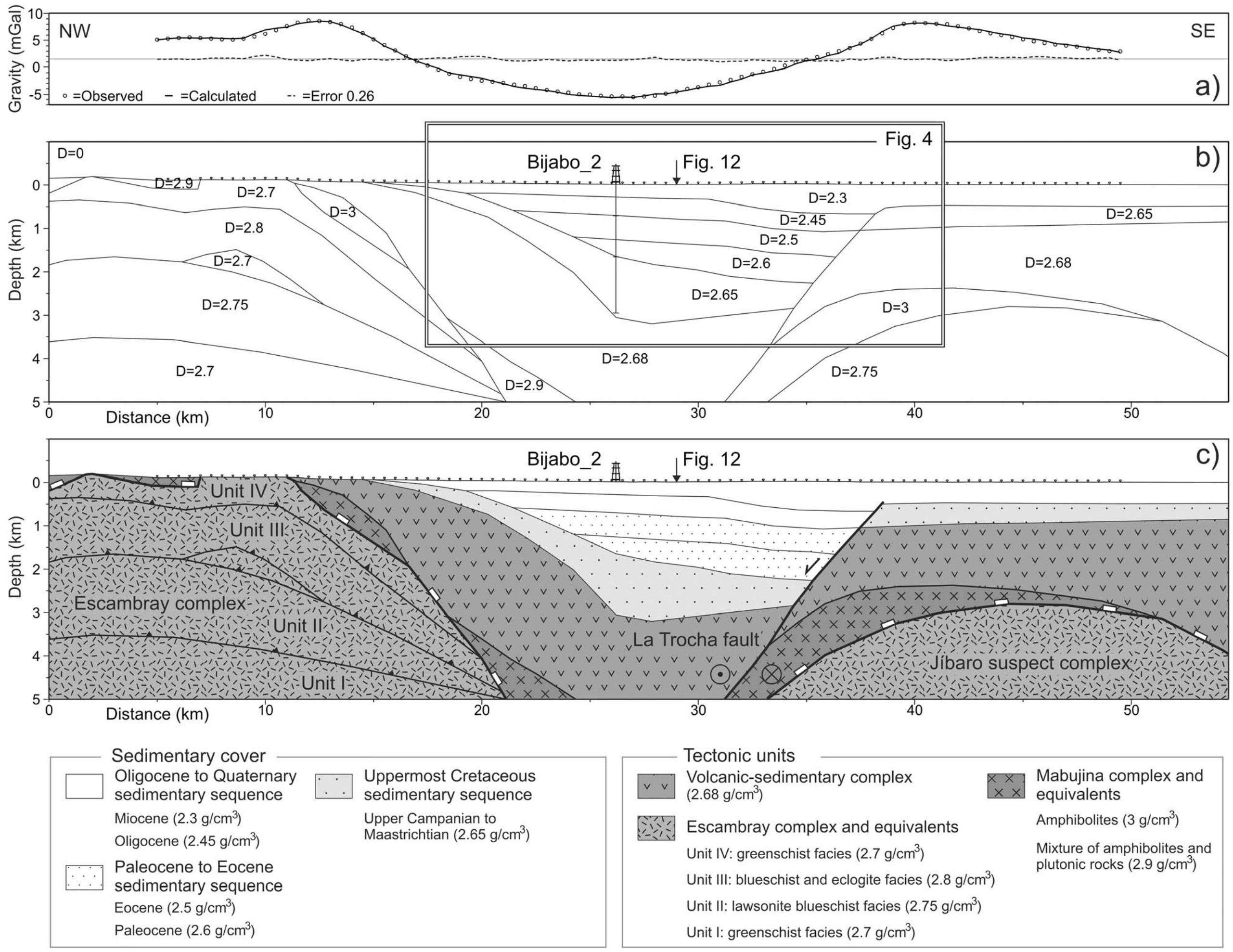

Figure 9. Two-dimensional transversal inversion gravity model of the southern La Trocha fault zone. Model includes the (a) gravity fit, (b) density model, and (c) interpretation panel. Structural and metamorphic arrangement of the Escambray complex is based on data from *Millán* [1997] and *Stanek et al.* [2006]. See location in Figure 8 and density data in Tables 1 and 2.

structural domain in central Cuba, is interpreted as an antiformal stack of several tectonic units that show an inverted metamorphism [see *Cruz-Orosa et al.*, 2012, and references therein]. The density range was assumed from mixtures of siliciclastic and calcareous metasediments with occasional metabasite intercalations while assuming an increase in the metamorphic grade upward. This interpretation is in keeping with data from *Millán* [1997], *Stanek et al.* [2006] and *García-Casco et al.* [2008] and suggests that there are repetitions in the metamorphic sequence. The contact between the Escambray complex and the overlain amphibolites and volcanic rocks is thought to be an extensional detachment, which allowed the exhumation of the Escambray complex (see descriptions by *Stanek et al.* [2006]). To the SE, the residual anomaly is ascribed to another structure that is equivalent to the Escambray complex in density and shape but does not crop out. This metamorphic complex is termed here the Jíbaro suspect complex and, like the Escambray, is interpreted as a dome below the amphibolites and volcanic arc rock. The Root Mean Square (RMS) error of this model is ±0.26 mGal.

[30] Figure 10 shows a NW-SE transect of the central La Trocha fault zone, from the eastern Cabaiguán Basin to the south of the Guayacanes high (Figures 2, 6 and 8). The observed gravity curve varies from −5.6 to 3.5 mGal and is flatter than in Figure 9. The geometry of the model is compiled almost entirely from the synthetic seismic section in Figure 5. Only the horizontal ends and bottom are inferred from fitting the residual gravity data. To the NW of the TGF, the sedimentary infill of the Cabaiguán Basin only includes the Paleocene to Eocene sequence and appears intensely folded. The structural high in the Taguasco_1 borehole is interpreted as an antiformal stack that involves volcanic rocks and the uppermost Cretaceous sedimentary sequence. By contrast, to the SE of the TGF, the sedimentary infill of the Central Basin includes Paleogene and Miocene sediments. The Oligocene to Quaternary sedimentary sequence is probably related to the normal component of the TGF, which cuts and displaces laterally the Taguasco_1 compressional structure. The southeastern anomaly is well adjusted by introducing a denser body —i.e., plutonic rocks— at depth. This interpretation is consistent with the outcropping of volcanic and plutonic rocks in the Guayacanes high

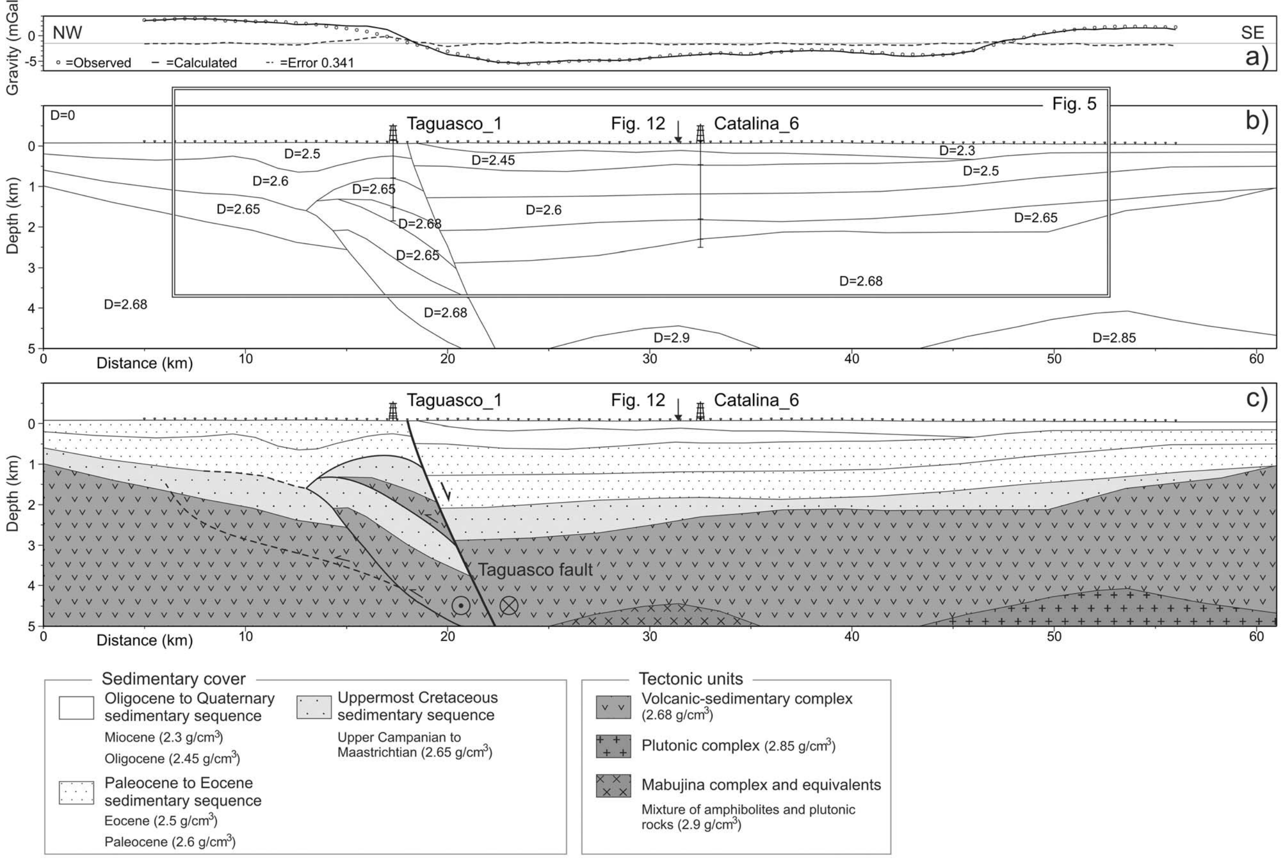

Figure 10. Two-dimensional transversal inversion gravity model of the central La Trocha fault zone. Model includes the (a) gravity fit, (b) density model, and (c) interpretation panel. See location in Figure 8 and density data in Tables 1 and 2.

(Figures 2 and 6). The LTF is not present at the southeastern end of this transect, strongly suggesting that this fault is attenuated and that a change in structural style occurs between the LTF and CTF. The RMS error of this model is ± 0.341 mGal and is mostly concentrated in the Taguasco_1 compressional structure. Although this error can be minimized, we prefer to leave it as it is in order to preserve the geometry from the seismic data.

[31] Figure 11 shows a NW-SE transect of the northern La Trocha fault zone, from the eastern Las Villas Mountain Range to the north of the Guayacanes high (Figures 3, 6 and 8). The gravity data vary from -5.3 to 4.6 mGal, showing an extensive negative anomaly between two gravity maximums. This model is constrained mainly by surface and borehole data and only partially by the available seismic data, which are poorly imaged probably because of the structural complexity of this area. The basin geometry has been interpreted as a compressional triangle zone that is deformed by strike-slip faults forming a block system. The central block looks like a small horst inside the main compressional structure. Sedimentary layers in the northwestern blocks consist of the Paleocene to Eocene sequence and are partially folded whereas in the southeastern blocks they include both the Paleocene to Eocene and Oligocene to Quaternary sequences that become thinner to the SE. This geometry together with surface geology demonstrates that major uplift and source area were located to the NW. The substratum structure was inferred from fitting the residual gravity data. To the NW of the ZTF it is well known that the Bahamas borderland sequences are overthrusted by the allochthonous serpentinite mélange and volcanic rocks that are thinner to the NW (see above and Figures 1 and 2). The substratum of the basin is mainly made up of volcanic rocks and the Cretaceous sedimentary sequence that have been sampled in several boreholes. In addition, the interpretation suggests that the Bahamas sequences are overthrusted by 3000 m of volcanic and sedimentary rocks. To the SE of the CTF, the basin substratum is cut at less than 500 m depth in the Cacahual_1 borehole. It is formed by an imbrication of volcanic, plutonic and ophiolitic rocks. Here, the Bahamas borderland sequences lie deeper than at the western end of this transect. The RMS error of this model is ± 0.311 mGal, but the models in Figures 9 and 10 are more robust because they are strongly constrained by seismic data.

[32] Figure 12 shows a SW-NE longitudinal transect of the La Trocha fault zone (Figure 8). The gravity data in this profile vary from -6.4 to 0.9 mGal, showing two large negative anomalies that are separated by a maximum in the structural high of Jatibonico. The gravity curve is fairly flat, with gradients that are abrupt only in the Jatibonico high and toward the ends of this transect. All the available structural constraints were introduced into the modeling process, including the intersections with the models in Figures 9, 10 and 11. The main structural constraints include the

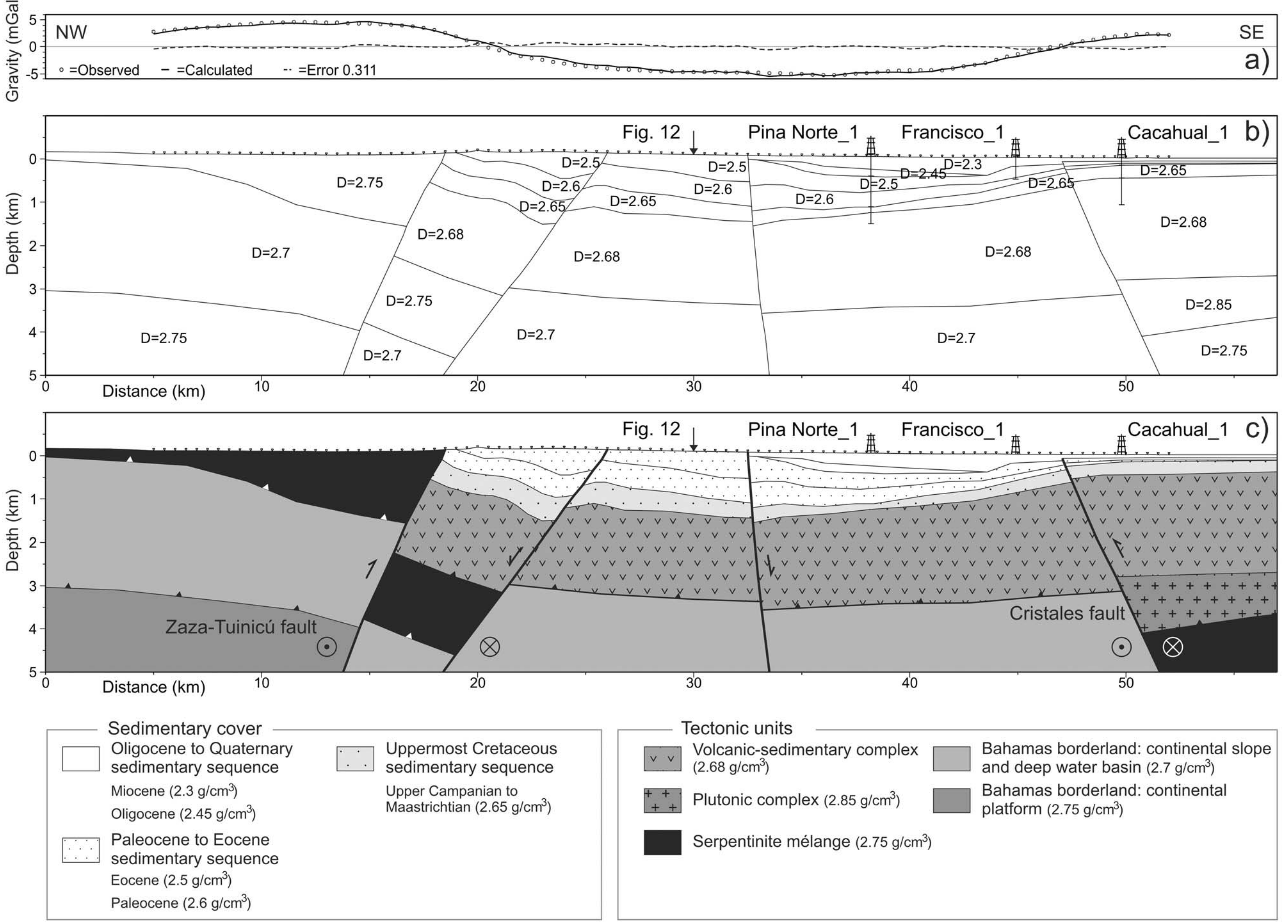

Figure 11. Two-dimensional transversal inversion gravity model of the northern La Trocha fault zone. Model includes the (a) gravity fit, (b) density model, and (c) interpretation panel. See location in Figure 8 and density data in Tables 1 and 2.

Jatibonico_78 and Morón Norte_1 boreholes, which reach a depth of 4436 and 5002 m, respectively. Two main structural zones are distinguished in the Central Basin. The zone located to the SW of the Jatibonico high is slightly deformed. The sedimentary infill ranges from the Paleocene to the Miocene and may exceed 3000 m in thickness. To the NE of the Jatibonico_78 borehole, the basin is deformed by some faults and its sedimentary infill is thinner than to the SW. Its sedimentary record is representative of the Paleocene to Oligocene time span —the Miocene succession is absent— and even the Paleocene and Eocene rocks crop out in some blocks. This depocenter is interconnected to the NE with the Morón Basin, which has a complete stratigraphic sequence —i.e., Paleocene to Miocene in age. The Morón Basin is the continuation of the foredeep basin in central Cuba as evidenced by its stratigraphic and structural features [*Iturralde-Vinent et al.*, 2008; *Cruz-Orosa et al.*, 2012]. Thicknesses in this basin are usually less than 2000 m. Volcanic rocks are predominant in the Central Basin substratum. However, it is thought that the Bahamas sequences are beneath the volcanic suite to the NE. In the Jatibonico structural high, the maximum gravity is well adjusted by a succession of volcanic, ophiolitic and metamorphic rocks, as observed in the Jatibonico_78 log (cf. in Figure 2b). The substratum in the northeastern area is interpreted as a thrust system that involves the Bahamas borderland sequences, which in turn are overthrusted by volcanic rocks. This interpretation is consistent with the log of the Morón Norte_1 borehole. A body of evaporites with a density of 2.25 g/cm^3 was introduced into the model to offset the negative gravity anomaly toward the NE end of this transect. This interpretation is in keeping with the Punta Alegre and Turiguanó outcroppings that can be considered as salt sheet structures [*Meyerhoff and Hatten*, 1968]. The interpretation of the substratum in the southwestern area is less robust because there are very few structural data to constrain the model. Some continuity between the Central and Ana María basins (Figure 2) is assumed in the model. However, the gravity interpretation is ambiguous because of the absence of structural data. Although the RMS error of this model is ± 0.27 mGal, it should be borne in mind that there are some areas where uncertainty is considerable.

4. Discussion

4.1. Geometry and Deformational Style

[33] Two areas with different features are distinguished in the La Trocha fault zone (Figures 2, 3, 6, 8 and 13). The

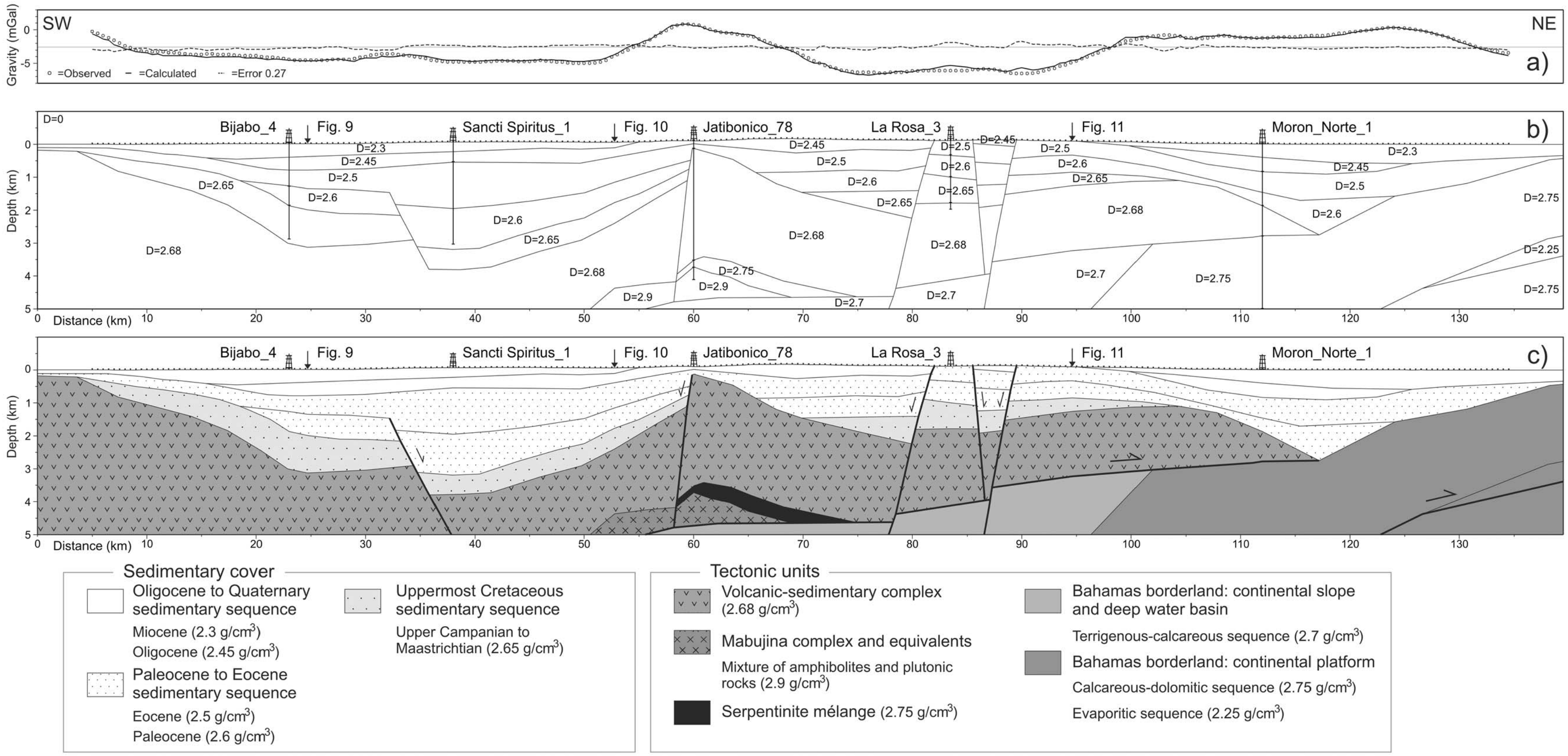

Figure 12. Two-dimensional longitudinal inversion gravity model of the La Trocha fault zone. Model includes the (a) gravity fit, (b) density model, and (c) interpretation panel. Density of evaporitic sequence was assumed from external data. See location in Figure 8 and density data in Tables 1 and 2.

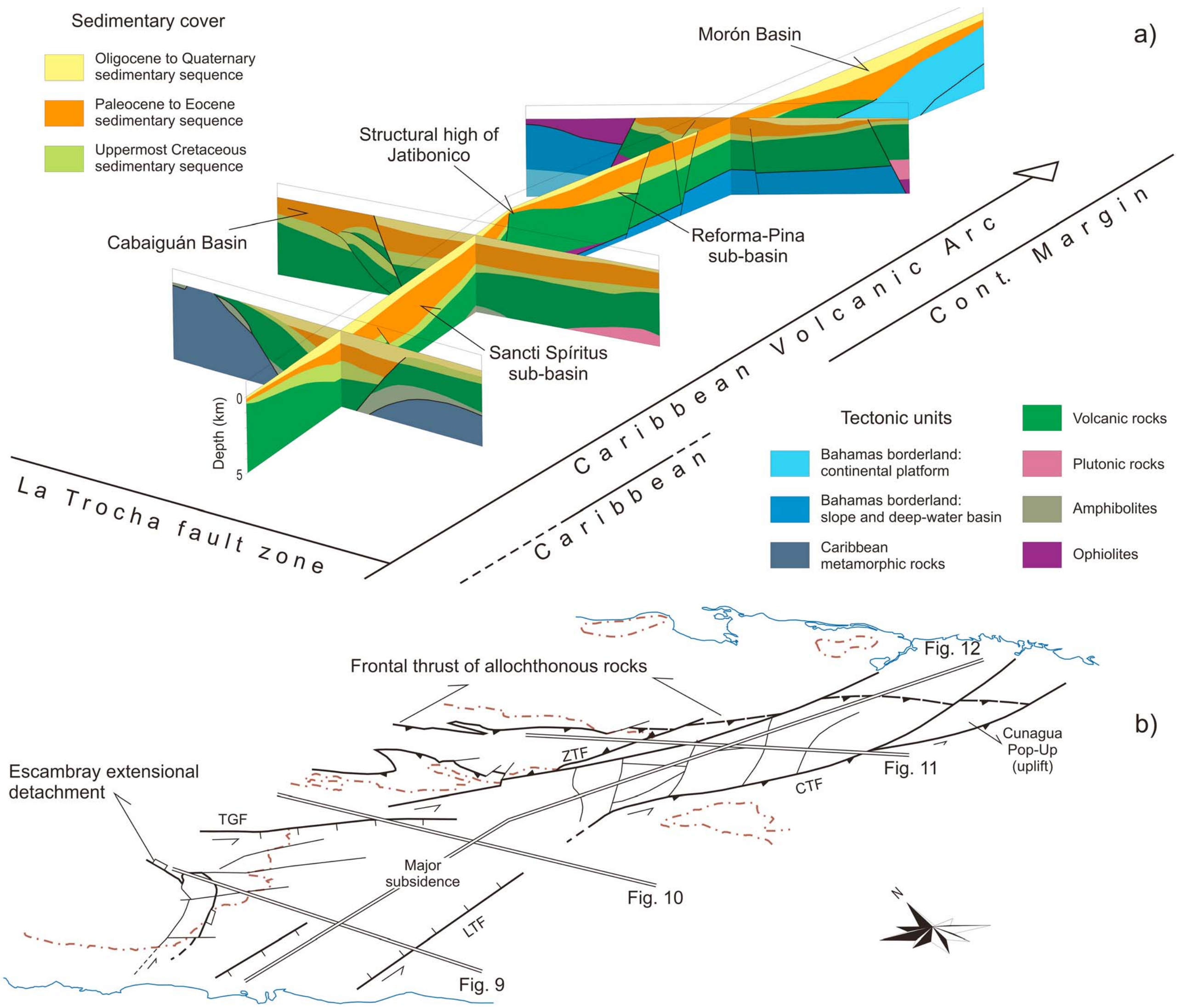

Figure 13. (a) The 3D panel and (b) structural arrangement showing geometry and major structural features of the La Trocha fault zone. See individual sections in Figures 9–12.

southwestern branch trends SW-NE and was developed under a transtensional regime. Displacement of major faults shows a normal component coeval with the main shortening stages during the formation of the Cuban Orogen. As shown in Figure 4, the LTF was very active between the Paleocene and the Eocene, and its transtensional character is corroborated by growth strata of this time span. Deformation in the LTF lasted until the earliest Miocene. Moreover, normal displacement of the TGF is younger than the Late Eocene, probably Late Oligocene-Miocene in age (Figures 5 and 10). The Taguasco structure had a transtensional character in the later phase, which is evidenced by a radical change in the deformation pattern on both sides of the TGF and by the overlap of compressional and extensional events. In addition, Figures 3 and 5 show a satellite system of minor strike-slip faults that record deformation during the Oligocene. On the other hand, the northeastern branch of the La Trocha fault zone trends WSW-ENE and developed in a transpressional regime. It is characterized by thrust and strike-slip faults. The ZTF was active after the Eocene as corroborated by the age of the sedimentary layers involved in the structure, whereas the CTF activity started later and continued to be active until the earliest Miocene. The ZTF could also have been active during the Oligocene and Miocene, but this cannot be confirmed because of the absence of the sedimentary record. The ZTF and CTF resulted in a compressional triangle zone that extends to the NE of the Jatibonico high, from the Reforma oilfield to the north of the Pina oilfield. Other minor strike-slip faults have combined to form a block system in this region (Figures 11, 12 and 13).

[34] In the Central Basin, the southwestward Sancti Spíritus depocenter forms a half-graben linked to the LTF (Figures 4, 9 and 13). The Sancti Spíritus depocenter records the maximum depth in the Sancti Spíritus_1 borehole, where it exceeds 3162 m. To the SW, it is thinner and its boundary with the Ana María Basin is uncertain. The depocenter ends in the structural high of Jatibonico to the NE (see above and Figures 12 and 13). This depocenter was connected to the Cabaiguán Basin until the latest Eocene, when the Taguasco structure began to form. It is thought that subsidence in the

southwestern part of the basin was related to a transtensional regime and controlled mainly by the LTF. By contrast, the northeastward area of the Central Basin constitutes a compressional triangle zone (Figures 11 and 13). The maximum depth of the basal unconformity (U_0) is in the Reforma oilfield and to the NE of the Pina oilfield, where it exceeds 1400 and 1500 m, respectively (Figures 2 and 6). The subsidence of this area occurred in a transpressional regime and was mainly controlled by the ZTF.

[35] The foregoing features strongly suggest that the Central Basin is a strike-slip polygenetic basin that evolved synchronously with a major fault zone in a dominantly convergent setting (see reviews by *Sylvester* [1988] and *Nilsen and Sylvester* [1995]). The basin was developed on the deformed volcanic arc suite, which in turn is allochthonous on the Bahamas borderland sequences. The main depositional areas in the Central Basin —i.e., the Sancti Spíritus and Reforma-Pina sub-basins (Figure 13)— evolved independently under different structural regimes and were controlled by the evolution of the La Trocha fault zone.

4.2. Structural Evolution

[36] The tectonic model of *Pindell et al.* [2005] was taken as the reference in order to integrate our data into the regional framework of the northwestern Caribbean (Figure 14). In addition, data from *Mann* [1997], *García-Casco et al.* [2008], and *Pindell and Kennan* [2009] were also used to enrich and update our discussion. A Pacific-origin model of the Caribbean Plate was assumed because it allows the integration of the geology of Cuba, Yucatan Basin and Cayman Trough more readily than the intraAmerican models [see *Pindell et al.*, 2006, and references therein]. This model demonstrates that the relative motion of the Caribbean Plate in relation to the North American Plate (CAR-NOAM relative motion) has rotated almost 40° clockwise since the latest Cretaceous. Relative motion shifted from a SW-NE direction (N43.5°E) in the latest Cretaceous (72 Ma) to a WSW-ENE direction (N66.2°E) at 56 Ma and subsequently to a W-E direction (N82.5°E) at 33 Ma [cf. *Sykes et al.*, 1982; *Dixon et al.*, 1998; *DeMets et al.*, 2000]. According to *Mann* [1997], shift of the relative motion was due to the tectonic escape that allowed the Caribbean Plate to enter the Proto-Caribbean realm between the North and South American plates. This rotation resulted in an increase in obliquity of collision and in the occurrence of a left-lateral wrench tectonics in the northwestern Caribbean Volcanic Arc. These regional changes are well recorded in the structure of the La Trocha fault zone. The evolution of plate-kinematics and structural pattern in this fault zone shows a similar trend (Figure 15).

4.2.1. Latest Cretaceous: Extension of Volcanic Arc?

[37] The main tectonic event, which occurred during the latest Cretaceous in the northwestern Caribbean realm, was the subduction-accretion of the Caribeana terrane [*García-Casco et al.*, 2008; *Pindell and Kennan*, 2009]. This event led to the cessation of the Cretaceous magmatic activity in Cuba during the Late Campanian and to the coeval deformation, uplift and partial erosion of the volcanic and ophiolitic rocks. According to *Pindell et al.* [2005], the Caribbean Volcanic Arc must have lengthened by an "en echelon" system of sinistral transfer faults (Figure 14a). These faults have been considered as precursors of the Pinar, La Trocha, Cauto, and other SW-NE striking Cuban faults, which presumably reactivated during the Paleogene collision [*Stanek et al.*, 2000]. Nevertheless, our data show that (1) the main faults of the La Trocha fault zone cut the uppermost Cretaceous sedimentary sequence, (2) the main syntectonic sedimentation occurred between the Paleocene and the Eocene, and that (3) there is no evidence of an older deformation event and subsequent reactivation during the Paleogene. Thus, the origin of the La Trocha fault zone is consistent with the Paleogene collision between the incipient Cuban Orogen and the Bahamas borderland.

4.2.2. Paleocene-Eocene: Collision With Bahamas

[38] The Paleogene arc-continent collision involved the extinct Caribbean Volcanic Arc and the North American continental margin. This collision resulted in the formation of a fold-and-thrust belt in the northern structural domain of the Cuban Orogen, a collision-related basin system, and in a set of SW-NE striking left-lateral faults that bordered some oblique fault zones.

[39] In the Paleocene, according to *Pindell et al.* [2005], the CAR-NOAM relative convergence trended SW-NE whereas the convergence between central Cuba and NOAM had a SSW-NNE trend. These authors also suggest that western and central Cuba evolved independently of the bulk of the Caribbean Plate and that difference in convergence direction produced a NW-SE extension in the Proto-Yucatan Basin (Figures 14b and 15). At this time (65–48 Ma), a SSW-NNE shortening (Z_1) took place in central Cuba [*Cruz-Orosa et al.*, 2012]. This shortening was responsible for the formation of a WNW-ESE striking fold-and-thrust belt in the Northern Deformation Belt and a set of strike-slip faults in the La Trocha fault zone (Figure 14e and 15). The SW-NE LTF behaved like a left-lateral normal fault and its main activity occurred between the Paleocene and the Middle Eocene, which is evidenced by more than 1200 m of growth strata (Figures 4 and 9). Normal displacement of the LTF is measured in 1.5 s of TWT in the seismic section in Figure 4 —cf. 1800 m in model in Figure 9— whereas left-lateral displacement is not quantifiable with available data. The WSW-ENE ZTF behaved like a left-lateral thrust fault as corroborated by age and relationships of the sedimentary layers involved in this structure (see above and Figures 2, 3 and 11). Thrust displacement of the ZTF exceeded 2000 m in the model in Figure 11 and left-lateral displacement was unquantifiable.

[40] Subsequently, the CAR-NOAM relative motion rotated clockwise and from the latest Paleocene to the Middle Eocene it trended WSW-ENE (Figures 14c and 15). In this time span, the last phase in the opening of the Yucatan Basin was related to an oceanic pull-apart extension [*Rosencrantz*, 1990; *Pindell et al.*, 2005] and the Cayman Trough began to form [*Rosencrantz et al.*, 1988; *Mann et al.*, 1995; *Leroy et al.*, 2000]. According to *Pindell et al.* [2005], the relative motion of the central Cuban blocks —i.e., the Las Villas and Camagüey blocks— in relation to the North American Plate had a SW-NE trend. During the Middle Eocene (48–37 Ma), a SW-NE shortening (Z_2) took place in central Cuba as is recorded by the development of a left-lateral shear and an "en echelon" folds system in the suture zone [*Cruz-Orosa et al.*, 2012] (Figure 14f). The LTF behaved like a normal fault in consonance with the Z_2 shortening whereas the ZTF continued as a left-lateral thrust fault. By this time the CTF was already active and the left-lateral motion

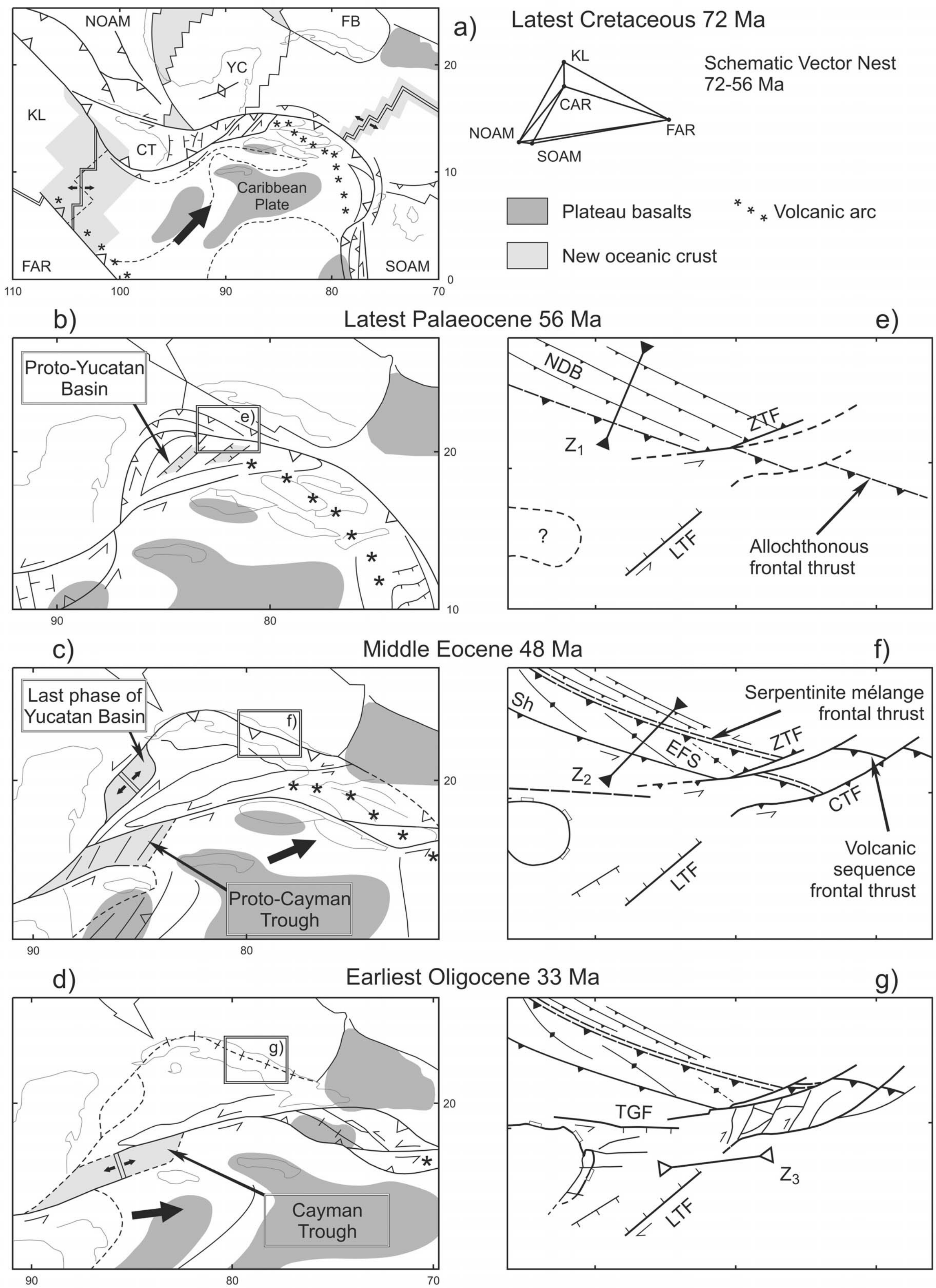

Figure 14. Comparison between (a–d) tectonic model of the northwestern Caribbean and (e–g) structural evolution of the La Trocha fault zone. Tectonic model is simplified from *Pindell et al.* [2005]: Caribbean Plate (CAR), North American Plate (NOAM), South American Plate (SOAM), Farallon Plate (FAR), Kula Plate (KL), Florida-Bahamas platform (FB), Yucatan block (YC) and Chortis block (CT). In structural frames: La Trocha fault (LTF), Zaza-Tuinicú fault (ZTF), Cristales fault (CTF), Taguasco fault (TGF), Northern Deformation Belt (NDB), left-lateral shear in the suture zone (Sh) and "en echelon" folds system (EFS).

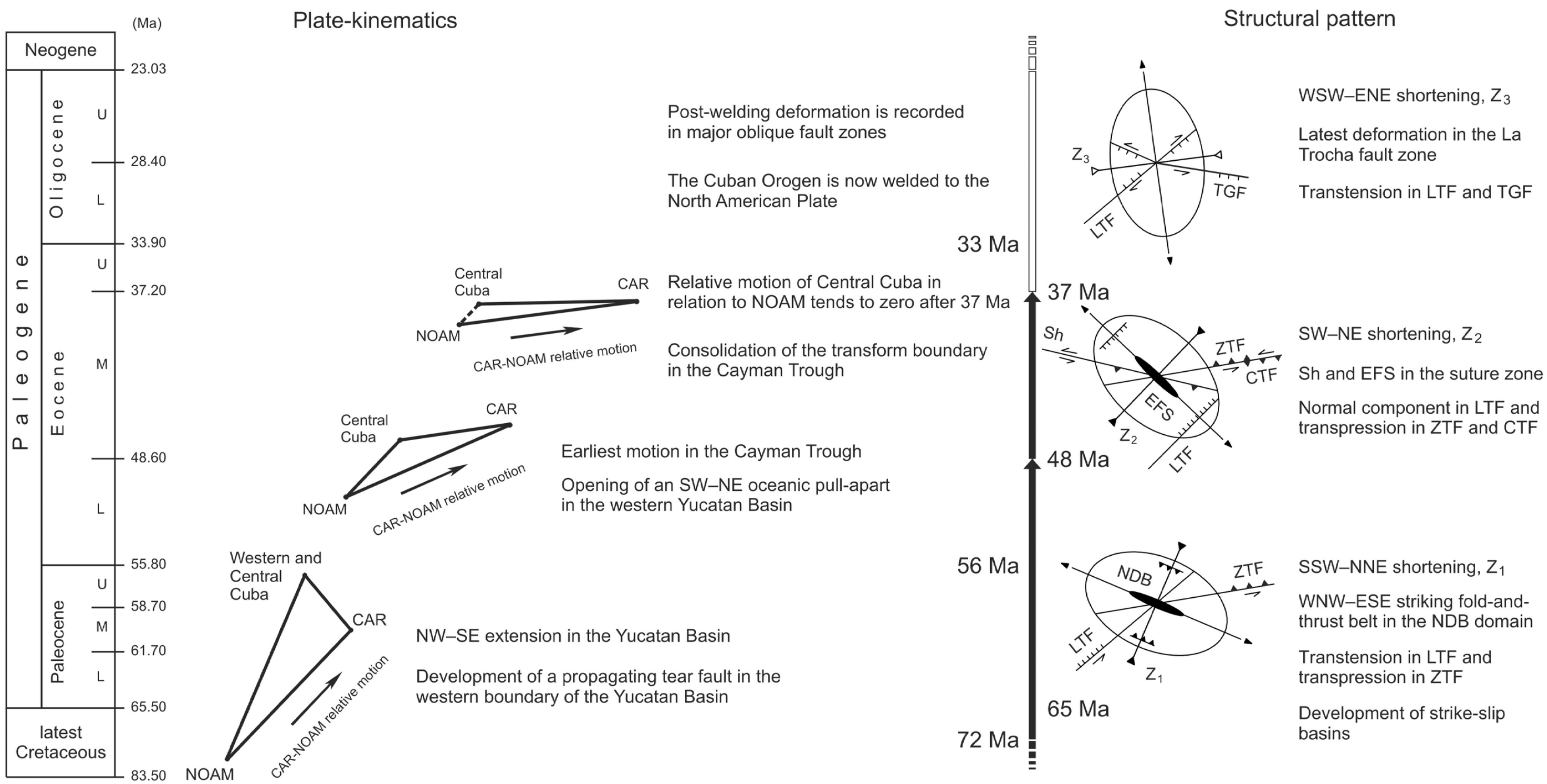

Figure 15. Relationships of plate-kinematics in the northwestern Caribbean with evolution of structural pattern in the La Trocha fault zone during the latest Cretaceous to Paleogene time span. Plate-kinematics is based on *Pindell et al.* [2005] and evolution of structural pattern is compiled from *Cruz-Orosa et al.* [2012]. Ages after *Gradstein et al.* [2004]. Caribbean Plate (CAR), North American Plate (NOAM), La Trocha fault (LTF), Zaza-Tuinicú fault (ZTF), Cristales fault (CTF), Taguasco fault (TGF), Northern Deformation Belt (NDB), left-lateral shear in the suture zone (Sh) and "en echelon" folds system (EFS). See details in text.

probably prevailed over the thrust component in this structure (Figure 11).

[41] In summary, during the Paleogene collision, the evolution of the structural pattern in the La Trocha fault zone reveals two phases of deformation that occurred in consonance with plate-kinematics of the northwestern Caribbean. The first phase, which occurred between the Paleocene and the Early Eocene (65–48 Ma), corresponds to a SSW-NNE shortening, giving rise to transtension of the LTF and transpression of the ZTF. The second phase, which took place during the Middle Eocene (48–37 Ma), corresponds to a SW-NE shortening that resulted in the normal component of the LTF and transpression in the ZTF and CTF. Surface and subsurface data corroborate both normal and thrust displacements of the main faults (see above and Figures 2–5 and 9–12). However, left-lateral displacement is deduced from the concordance between plate-kinematics and structural features, but this is not quantifiable.

4.2.3. Post-Middle Eocene: Welding of Central Cuba

[42] Since the formation and consolidation of the current transform boundary in the Cayman Trough, the CAR-NOAM relative motion has followed a W-E direction [*Sykes et al.*, 1982]. The syn-thrusting sediments of central Cuba suggest that collision lasted until the latest Middle Eocene (ca.37 Ma), when post-thrusting sedimentation started [*Iturralde-Vinent et al.*, 2008; *Cruz-Orosa et al.*, 2012]. Central Cuba was then welded to the North American Plate and the post-welding deformation was recorded in some strike-slip faults along the southern Axial Zone of the orogen and in major oblique fault zones (Figures 14d and 15). This post-welding deformation was consistent with a WSW-ENE shortening (Z_3) and reflects activity in the transform boundary of the Cayman Trough. Some normal post-Eocene displacement of the LTF is recorded in seismic sections (e.g., Figure 4). This observation and the relative orientation between this fault and Z_3 shortening suggests that the LTF could have behaved like a normal fault with a minor dextral displacement. Dextral displacement is not quantifiable. However, total horizontal displacement remains left-lateral. Normal displacement of the TGF cuts the antiformal stack of the Taguasco structure and is measured in 1.0 s of TWT in Figure 5 —cf. 1000 m in Figure 10. In addition, some flower structures that cut the Paleocene-Oligocene succession are recorded in the seismic section of the southern branch of the La Trocha fault zone (Figure 5), whereas some secondary strike-slip faults occurred inside the northern branch of this fault zone (Figures 11, 12, and 14g).

4.3. Implications for Plate Tectonics

[43] The foregoing structural evolution of the La Trocha fault zone is consistent with plate-kinematics proposed by *Pindell et al.* [2005]. This evolution lends support to the view that the origin of this fault zone was coeval with extension in the Yucatan Basin [*Rosencrantz*, 1990, 1996; *Pindell et al.*, 2005] and that oblique collision occurred in the northwestern Caribbean during the Paleogene. The oblique collision produced a fold-and-thrust belt in the northern structural domain of the Cuban Orogen [*Saura et al.*, 2008; *van Hinsbergen et al.*, 2009; *Cruz-Orosa et al.*, 2012]. The NW-Caribbean realm then evolved as a microplate isolated from the Caribbean and North American plates. This hypothesis is corroborated by (1) the occurrence of a latest Cretaceous to Paleogene convergence (subduction-accretion-collision), which is well documented in the Cuban Orogen; (2) the development of the Yucatan Basin in situ between the Caribbean and North American plates; and by (3) the evolution of Cuban terranes independently of the Caribbean Plate. Subsequently, the origin and consolidation of the current transform boundary in the Cayman Trough resulted in the welding of the Cuban microplate (cf. the Yucatan Basin and Cuban Orogen) to the North American Plate during the Eocene.

[44] The La Trocha fault zone may have behaved like a major transfer zone and the observed structural differences in the Las Villas (LVB) and Camagüey (CMB) blocks lends support to this assumption (Figure 1). Both blocks have a similar constitution as regards the major tectonic units that compose them despite significant differences in structural features, relationships and intensity of deformation, which suggests that structural and tectonic evolution were also different. In the Northern Deformation Belt of the LVB, the Bahamas borderland rocks are imbricated in a thin-skinned thrust system that involves continental slope/deep water basin and continental platform series [*Cruz-Orosa et al.*, 2012]. However, there is no conclusive evidence for nappe accretion during the Paleogene collision in the CMB [*van Hinsbergen et al.*, 2009]. The suture zone in the LVB was affected by a left-lateral shear and an “en echelon” folds system that is absent in the CMB. The volcanic arc occupies the Axial Zone of the orogenic belt and is strongly folded and thrusted in the LVB, whereas deformation is lower in the CMB [*Tait et al.*, 2009; *Stanek et al.*, 2009]. The Escambray Metamorphic Complex crops out in a tectonic window below the volcanic arc in the LVB, whereas the metamorphic rocks do not crop out in the CMB [*Bush and Shcherbakova*, 1986; *Pardo*, 1996; *García-Casco et al.*, 2008]. All these criteria strongly suggest that the La Trocha fault zone was a major tectonic limit.

[45] Our results corroborate and constrain the tectonic models proposed by *Mann et al.* [1995], *Gordon et al.* [1997] and *Leroy et al.* [2000] and are in line with the southeastward migration of the Cuban front collision. The main discrepancy between our data and the aforementioned models concerns the age of activity in the La Trocha fault zone. Although these models suggest that activity started in the Eocene, our data demonstrate that this activity started in the Paleocene. The southeastward migration responds to the continuous updating of the convergence direction between the Caribbean Volcanic Arc and the North-American continental margin. The convergence direction was affected by the rotation of the CAR-NOAM relative motion and by the increase in obliquity that resulted from the tectonic escape of the Caribbean Plate between the North and South American plates [*Mann*, 1997].

5. Conclusions

[46] In the light of the foregoing discussion, the following conclusions may be drawn:

[47] (1) The La Trocha fault zone behaved like a major left-lateral transfer fault zone in central Cuba. Two structural zones are distinguished in this fault zone. The southwestern branch strikes SW-NE and resembles a half-graben that developed under a transtensional regime, whereas the northeastern branch

strikes WSW-ENE and is a triangle zone in a transpressional regime. Both transtensional and transpressional regimes are consistent with the shortening that generated the central Cuban orogenic belt and are corroborated by normal and thrust displacements of the main faults. Different regimes are associated with different geometries —i.e., strike of the main faults.

[48] (2) The Central Basin is a strike-slip polygenetic basin that evolved at the same time as the La Trocha fault zone. Different depositional areas are distinguished. Subsidence was mainly controlled by the LTF in the Sancti Spíritus sub-basin whereas it was controlled by the ZTF in the Reforma-Pina sub-basin. Our modeling suggests that the Bahamas rocks lie under 3000 m of volcanic sequence in the northeastern branch of the Central Basin. This hypothesis may be attractive for conducting hydrocarbon exploration in the zone given that the Bahamas continental slope and deep-water basin sequences are considered as a major petroleum play.

[49] (3) Evolution of the La Trocha fault zone is marked by the clockwise rotation of shortening directions in central Cuba. Between the Paleocene and the Early Eocene (65–48 Ma), a SSW-NNE shortening (Z_1) led to the formation of the WNW-ESE striking fold-and-thrust belt and to the set of SW-NE strike-slip faults. In the La Trocha fault zone, Z_1 gave rise to the transtensional and transpressional regimes that are corroborated by normal and thrust components of the LTF and ZTF, respectively. Subsequently, during the Middle Eocene (48–37 Ma), Z_2 shortening trended SW-NE. This shortening was recorded by a left-lateral shear and an "en echelon" folds system in the suture zone of the central Cuban orogenic belt. The LTF then behaved like a normal fault, the ZTF continued as a left-lateral thrust fault and the left-lateral motion probably prevailed in the CTF. In the post-Middle Eocene (37 Ma), shortening (Z_3) trended WSW-ENE, reflecting activity in the transform boundary of the Cayman Trough. This shortening was much smaller than the previous shortening —i.e., Z_1 and Z_2— and resulted in transtensional activity of the LTF, TGF and other minor faults inside the fault zone. The proposed evolution is consistent with plate-kinematics and suggests that the formation of the La Trocha fault zone was coeval with the Cuban orogeny.

[50] (4) The origin and evolution of the La Trocha fault zone and Central Basin is consistent with the Paleogene collision between the Caribbean Volcanic Arc (i.e., the Cuban sector) and the Bahamas borderland, and with plate-kinematics proposed by *Pindell et al.* [2005]. Central Cuba was part of a microplate and the La Trocha fault zone probably behaved like a major tectonic limit. The welding of central Cuba to the North American Plate occurred in the latest Middle Eocene (ca. 37 Ma). Thus, the post-Eocene deformation recorded in the Cuban fault zones and in the Cuban foreland should be considered as a post-welding deformation.

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