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Cenozoic tectonic history of the North America-Caribbean plate boundary zone in western Cuba

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Abstract. Structural studies of well-dated Jurassic to lower Miocene rocks in western Cuba constrain the sequence of structural events affecting this oblique collisional zone between the late Cretaceous island arc and the Jurassic-Cretaceous North America passive margin in the southeastern Gulf of Mexico and Straits of Florida. Results of detailed mapping and collection of fault slip data at 34 sites define a regionally consistent, five phase tectonic model for the period from the late Paleocene to the post-early Miocene. During the late Paleocene to the early Eocene, the Cuban island arc collided with the North American passive margin (Bahamas Platform). Northwest-ward overthrusting during the collision defines tectonic phase I. A NNE-SSW compression concurrent with early Eocene left-lateral strike-slip faulting along the Pinar fault zone defines phase II. This result is consistent with structural mapping showing sinistral shear within the 065° striking Pinar fault zone. An ENE-WSW to E-W compression defining phase III overprinted phase II faults in the lower Eocene and older rocks. Post-early Miocene normal faulting characterizes phase IV. Inversion of fault slip data indicates two contemporaneous directions of tension of 120 and 170. Strike-slip faults that overprint phase IV normal faults yield a 120 compression (phase V). The direction of compression associated with the arc/continent collision rotates clockwise from NW-SE in the late Paleocene/early Eocene (phase I), to NNE-SSW (phase II) and to ENE-WSW by the middle Eocene (phase III). The rotation in the compression direction occurred because the arc turned toward an oceanic area in the present-day area of central and eastern Cuba. Progressive collision led to complete subduction of the remnant oceanic crust by middle to late Eocene time.

Introduction

Collision between arcs and continents leads to orogenesis and the reorientation of arcs toward a nearby oceanic margin or "free face" [*McKenzie*, 1972; *Burke and Sengör*, 1986]. The Cenozoic collisional history of the Caribbean arc has been proposed as an example of the tectonic escape process. Northwestward movement of the Caribbean plate was opposed by the collision between the Caribbean plate and Bahamas Platform [*Malfait and Dinkelman*, 1972; *Rosencrantz*, 1990] (Figure 1b) and yielded to Eocene to Recent east-northeastward motion in eastern Cuba, Hispaniola, and Puerto Rico [*Mann et al.*, 1991, 1995] (Figure 1a). Transtensional left-lateral strike-slip faults beneath the Yucatan basin and in the Cayman Trough allowed continued clockwise rotation, collision, and eastward motion toward a free face in the Atlantic Ocean. The negative buoyancy of the subducted Jurassic-Cretaceous age Atlantic Ocean lithosphere [*Royden*, 1993] was probably the driving force for the change in plate convergence direction and continued motion of the Caribbean arc toward the free face to the east

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In this study we describe an initial, quantitative test of the escape hypothesis by a systematic study of brittle faults deforming well-dated Jurassic to Miocene sedimentary rocks in the western Cuban fold-thrust belt that formed in Paleocene/early Eocene time. Paleostress analysis combined with detailed biostratigraphy is necessary to quantify the paleotectonic history. Western Cuba was selected for detailed study for the following reasons: (1) its tectonic position at the most northerly limit of the circum-Caribbean fold-thrust belt; (2) its well-exposed Jurassic-Neogene marine sedimentary rocks, and (3) the close spatial association of folds, thrust faults, and strike-slip faults. A parallel biostratigraphic study described elsewhere [*Bralower and Iturralde-Vinent*, 1997] was carried out to better constrain the ages of critical rock units studied.

Tectonic Setting of the Caribbean and Cuba

Present-Day Tectonic Setting

Cuba is the largest island in the Greater Antilles and exposes the most extensive and continuous Jurassic to Neogene stratigraphic sections in the northern Caribbean, Bahamas, and southern Gulf of Mexico region. A fold-thrust belt was formed by the collision of the Caribbean and North America plates during early Tertiary time and is semicontinuous along the length of the island. The majority of Cuba is located outside the 200 km wide zone of active strike-slip deformation and related earthquakes between the Caribbean and North America plates

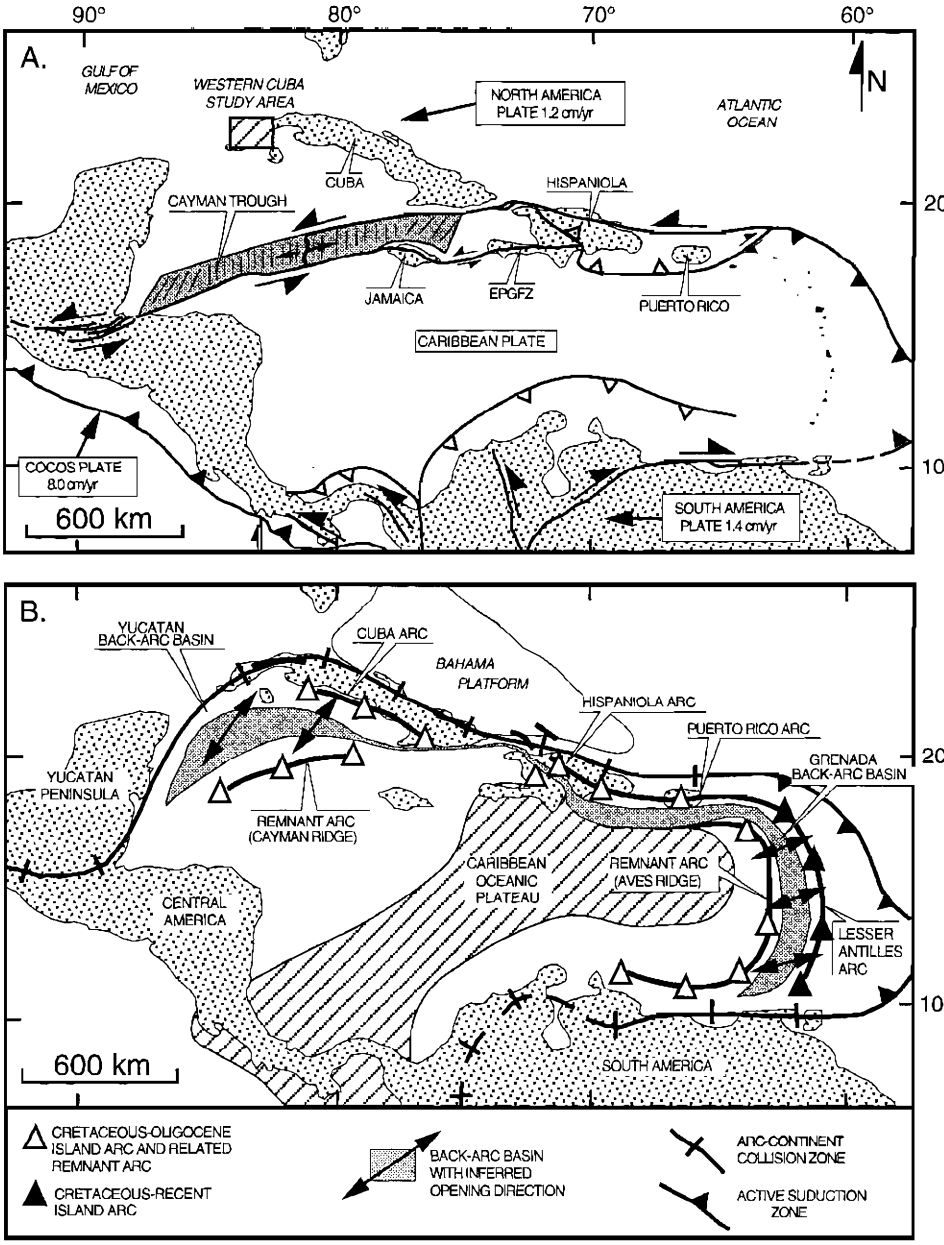

Figure 1. (a) Present-day plate boundary faults of the Caribbean plate modified from *Mann et al.* [1991]. Directions and rates of plate motion relative to the Caribbean plate are from *DeMets et al.* [1990]. Abbreviation EPGF is for the Enriquillo Plantain Garden fault. (b) Four main tectonic elements of the Late Cretaceous-Eocene island arc/collisional plate boundary separating the North America and South America plates: Late Cretaceous oceanic plateau; Late Cretaceous-Recent island arc or Great Arc of the Caribbean; Late Cretaceous-Eocene back-arc basin, and Jurassic-Recent Bahamas carbonate platform. Cuba formed as the result of an early Tertiary collision between the Great Arc and the Bahamas carbonate platform. Arrows indicate inferred direction of opening in the Yucatan back-arc basin [*Rosencrantz*, 1990] and the Grenada back-arc basin [*Bird et al.*, 1993].

(Figure 1a). A minimum of 1100 km of left-lateral offset along this active boundary since the Eocene has produced the Cayman Trough, an elongate east-west striking, pull-apart basin floored by oceanic crust [*Rosencrantz et al.*, 1988]. The Caribbean plate is presently bounded on the east and west by subduction zones. In the east, Atlantic Ocean lithosphere is subducted beneath the Lesser Antilles arc, while in the west, Pacific Ocean lithosphere is subducted beneath the Central America arc.

Great Arc of the Caribbean

Western Cuba occupies the northernmost segment of an early Cretaceous to Recent island arc chain that extends from western Cuba to the north coast of South America (Figure 1b). The northern, or Greater Antilles, segment of the arc that includes the islands of Cuba, Hispaniola, Puerto Rico, and the Virgin Islands has been extinct since its collision with the

Bahamas Platform in late Paleocene to earliest Oligocene time. Major pulses of collision were broadly diachronous and occurred in late Paleocene/earliest Eocene time in western Cuba [*Bralower and Iturralde-Vinent*, 1997], early to middle Eocene time in Central Cuba [*Pardo*, 1975; *Hempton and Barros*, 1993; *Hatten et al.*, 1988, also unpublished report, 1958], middle Eocene to Recent in Hispaniola [*Mann et al.*, 1991], and late Eocene to early Oligocene time in Puerto Rico [*Dolan et al.*, 1991] (Figure 2a). *Rosencrantz* [1990] and *Mann et al.* [1995] proposed that collisions in Cuba and Hispaniola were coeval with the formation of left-lateral strike-slip fault systems and transtensional basins of Paleocene to Recent age in the Yucatan basin, Cayman Trough, and along the Enriquillo-Plantain Garden fault zone (Figure 1a).

Because all segments of the Caribbean arc initiated during the early Cretaceous and exhibit lithologic and geochemical similarities, several groups of workers have interpreted circum-Caribbean island arc rocks as a continuous volcanic arc chain that ringed a Late Cretaceous Pacific oceanic plateau formed during Early Cretaceous time and swept westward into the present-day Caribbean region during latest Cretaceous and Early Cenozoic time [*Malfait and Dinkelman*, 1972; *Pindell and Barrett*, 1990] (Figure 1b).

Island arc activity was accompanied by back-arc basin formation in the Yucatan and Grenada basins (Figure 1b). Marine heat flow measurements and depth to basement calculations using marine seismic profiles from the Yucatan back-arc basin southwest of Cuba suggest that ocean floor in the western part of the basin formed during a brief period of northeastern, transtensional strike-slip faulting between Paleocene and early Eocene time [*Rosencrantz*, 1990].

Geologic Framework of Western Cuba

Two Components of Cuban Geology

Cuba consists of two distinct suites of rocks that have been juxtaposed by northward and northeastward verging thrust faults of Paleocene-Eocene age.

1. The Cuban allochthon consists of Cretaceous arc and ophiolite-related metamorphic, sedimentary, and volcaniclastic rocks that formed along the leading edge of the exotic Caribbean plate and overthrust the passive margin of North America in Paleocene-Eocene time (Figure 2a). No in situ magmatic rocks younger than Campanian have been reported in western and central Cuba [*Iturralde-Vinent*, 1994] although arc rocks as young as middle Eocene have been found in situ in the Sierra de Maestra of eastern Cuba [*Jakus*, 1983]. Northwest to southeast younging in the age of arc rocks and deformation [*Hatten et al.*, 1988, also unpublished report 1958; *Hempton and Barros*, 1993; *Calais and Mercier de Lépinay*, 1995] is consistent with the progressive arc termination and deformation interpretation model shown by *Mann et al.* [1995] (Figure 2a).

The Cuban ophiolite and arc belt appears to strike off the south central coast of Cuba before reaching western Cuba and forms a prominent, linear gravity and magnetic high on the shallow shelf area south of Cuba [*Rosencrantz*, 1993]. The ophiolite-arc belt has been interpreted by most workers as a Cretaceous island arc that collided and overthrust partly coeval but distinctly different sedimentary facies of the passive margin that include carbonate, clastic, and evaporite rocks containing little or no arc detritus [*Wassall*, 1957; *Pardo*, 1975; *Gealey*, 1980]. At one locality in the thrust belt of north central Cuba, *Renne et al.* [1989] identified and dated Grenville age continental crust that was evidently transported as fragments in front of the Caribbean arc as it migrated in between North and South America. Paleomagnetic data from mid-Cretaceous arc rocks of central Cuba suggest that the Cuban arc was transported northward as part of the Caribbean plate before its Eocene accretion to North America [*Renne et al.*, 1991; *Bazhenov et al.*, 1996]. Northward overthrusting of the Cuban allochthon over the passive margin is indicated by the presence of tectonic windows through which unmetamorphosed and metamorphosed passive margin rocks crop out [*Hatten et al.*, 1988; *Rosencrantz*, 1993] (Figure 2a).

2. The passive margin sequence of North America consists of a Jurassic-Cretaceous carbonate platform sequence that is now exposed as a fold-thrust belt in low hills and mountains along the northwestern and north central edge of the island adjacent to the Bahamas Platform (Figure 2a) which *Burke* [1988] recognizes as extended continental crust. Seismic profiling in offshore areas and drilling in central Cuba have shown that the deformed onland sections correlate to less intensely deformed sections mapped and drilled offshore [*Ball et al.*, 1985; *Hempton and Barros*, 1993; *Rosencrantz*, 1993; *Walles*, 1993]. In western Cuba this sequence is exposed in the Sierra de Guaniguanico window and the much smaller Martin Mesa window to the east (Figure 2b). Seismic reflection exploration by Russian and Cuban geologists has determined that exposed rocks of the Sierra de Guaniguanico may be present beneath great thicknesses of Oligocene to Recent clastic and carbonate sedimentary rocks in areas outside of the Guaniguanico and Martin Mesa windows (Figure 2c). For example, a 2 km thick Oligocene-Recent section of carbonate and clastic rocks is present in the Los Palacios basin and a 5 km thick section of mainly clastic rocks unconformably overlies northwest-verging thrusts along the northern coast and shelf area of western Cuba [*García-Sánchez*, 1987]. The asymmetry of thickness distribution and the northern, largely offshore foredeep has been interpreted by *Angstadt et al.* [1985] and *Denny et al.* [1994] as a foredeep basin formed during and after a Paleocene-Eocene northward verging thrust event.

Belt Structure of Western Cuba

The exposed passive margin sequence of North America in the Guaniguanico window of western Cuba has been subdivided by *Pszczólkowski* [1987, 1994a] into four lithologically distinct yet coeval tectonostratigraphic belts that are all abruptly truncated to the south by the Pinar fault zone (Figure 2b).

Los Organos belt. This belt occupies the western, topographically lower two thirds of the Sierra de Guaniguanico window (Figure 2b). Basal sedimentary facies of the belt (San Cayetano Formation) record Early to Late Jurassic clastic shallow water deposition in fluvial and deltaic settings (Figure 3). These rocks grade upward into dark gray to black micritic limestone and shale of the Jagua Formation of Oxfordian age that in turn grades upward into a fine-grained, locally dolomitized, open water limestone of the Guasasa Formation of Oxfordian to Cenomanian age. The Los Organos belt was imbricated in Paleogene time into a series of flat-lying nappes [*Piotrowska*, 1987; C.W. Hatten, unpublished report, 1957]. The belt exhibits a large domal structure formed by gentle folding during or after thrusting. The Pinar 1 well drilled at the approximate center of the Los Organos belt and dome (Figure 2c) penetrated

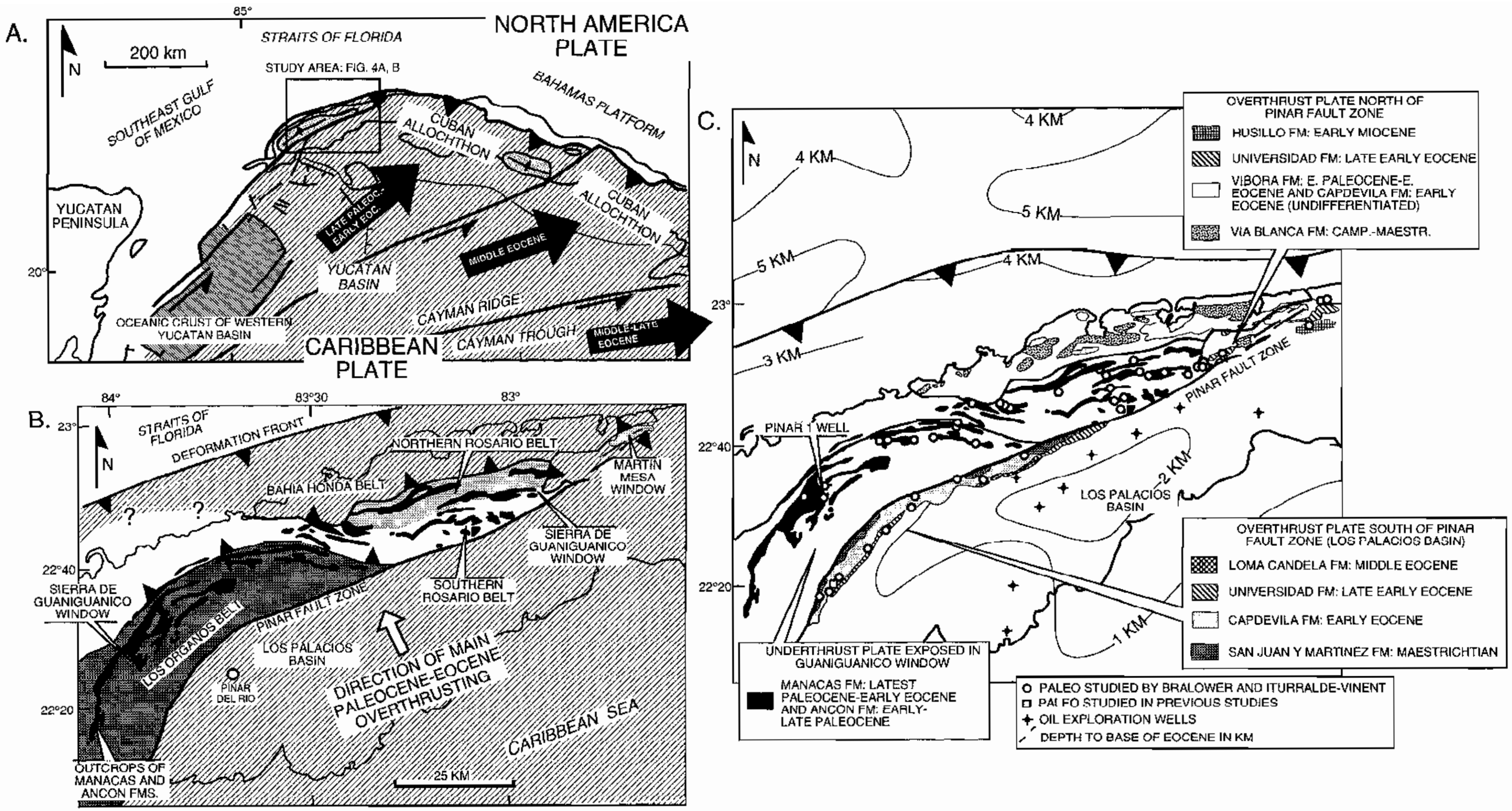

Figure 2. (a) Tectonic map of Cuba and the Yucatan basin based on *Rosencrantz* [1990]. Lined area represents rocks of the overthrusting Cuban Cretaceous arc and Paleocene-Eocene back-arc basin (i.e., leading edge of Pacific-derived Caribbean plate). Paleocene-Eocene? oceanic crust produced during back-arc opening behind the northeast facing Caribbean island arc is shown in gray. Unshaded area represents the underthrust passive margin of the North America plate (Bahamas carbonate platform and slope). Arrows represent inferred directions of Caribbean overthrusting and the inferred ages of thrusting in these directions. Tectonic windows expose both metamorphosed and unmetamorphosed sedimentary rocks of the Bahamas Platform and slope and suggest south to north overthrusting of the north facing Cuban arc over the margin. Box shows location of study area in Figure 2b. (b) Map of area studied in western Cuba showing extent of overthrust Cuban Cretaceous arc (lined pattern) and underthrust passive margin of North America exposed in the Sierra de Guaniguanico tectonic window. Nomenclature and definition of metamorphic and sedimentary margin rocks of Late Jurassic-Cretaceous age are from *Pszczółkowski* [1994a]. Direction of overthrusting shown is inferred from the fault studies reported here. (c) Map showing locations of samples (open circles) of key prethrusting, synthrusting, and postthrusting stratigraphic units dated paleontologically by *Bralower and Iturralde-Vinent* [1997] to bracket the age of deformation. Boxes summarize the stratigraphic units from three main tectonic areas sampled during this study: overthrust Caribbean plate north and east of the Pinar fault zone; overthrust Caribbean plate south of Pinar fault zone (Los Palacios belt), and underthrust North America plate in Sierra de Guaniguanico window. Contours (from inset map by V.I. Marakov and F. Formell on tectonic map compiled by *Pushcharovskiy* [1989]) are derived from exploration wells shown and seismic reflection data and represent depth in km to base of Eocene clastic rocks that largely post-dated collision.

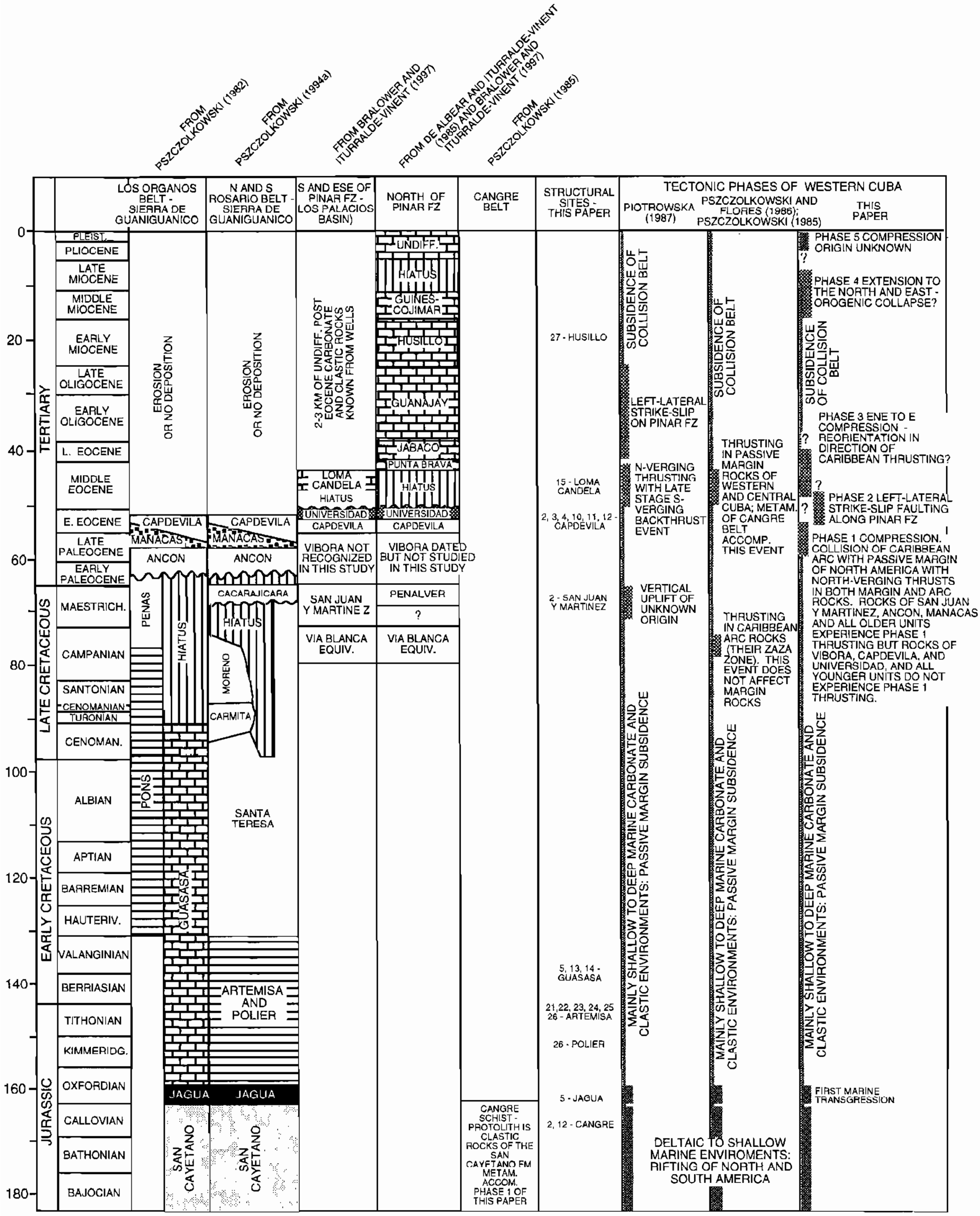

Figure 3. Summary of the age and general lithology of major stratigraphic units from the Sierra de Guaniguanico, Los Palacios basin, and area north of the Pinar fault zone studied for their micropaleontological content by *Bralower and Iturralde-Vinent* [1997] and for their deformational history in this paper. Numbered structural sites and the formation studied are indicated in the center column. The three columns to the right compare previous interpretations by *Piotrowska* [1987] and *Pszczólkowski and Flores* [1986] and *Pszczólkowski* [1985; 1994a] with the chronology and style of tectonic phases presented in this paper. Note that our collisional and strike-slip phases that terminated passive margin subsidence are somewhat older than previous workers and that the post-strike-slip phases we propose were not recognized by previous workers.

4200 m of thrust sheets of passive margin sedimentary rocks similar to those exposed at the surface but did not encounter arc or ophiolitic rocks [*Pszczólkowski*, 1994b]. This observation is consistent with the concept that arc and ophiolitic rocks of the Cuban allochthon are part of the structurally higher, overthrusting plate [e.g., *Wassall*, 1957; Gealey, 1980]. To the south the Organos belt and dome are sharply truncated by the linear Pinar fault zone (Figure 4).

Southern Rosario belt. This belt occupies an arcuate, topographically higher area across the north central part of the Sierra de Guaniguanico window (Figure 2b). A small segment of the northwestern part of this belt lies in fault contact with structurally higher ophiolites of the overlying Bahía Honda zone [*Pszczólkowski*, 1994b]. The belt includes deep marine carbonate and clastic facies ranging in age from Late Jurassic-Early Cretaceous (Artemisa, Santa Teresa Formations) through more fragmented carbonate lithologies of the Late Cretaceous (Carmita, Moreno, Cacarajicara Formations) (Figure 3). The youngest, prethrust deepwater formation in this belt is the Ancón Formation of early-late Paleocene age [*Bralower and Iturralde-Vinent*, 1997]. The Southern Rosario belt contains several nappes that lie on basal thrusts dipping gently northward. To the north, the belt extends offshore; to the south the belt is sharply truncated by the linear Pinar fault zone (Figure 4).

Northern Rosario belt. This belt forms the easternmost and topographically highest belt of the Sierra de Guaniguanico (Figure 2b). A small segment of the northern part of this belt lies in fault contact with ophiolites of the overlying Bahía Honda zone. Lithologies include deep water carbonate and clastic facies of similar description and age to those in the Southern Rosario belt but generally finer-grained and of more distal facies. As we did not study the structure of this belt, we do not describe its stratigraphy or refer to it again.

Overthrust Caribbean arc and ophiolite-related rocks. These rocks are grouped into different belts referred to as the Zaza terrane, the Bahía Honda belt, or the Los Palacios belt [*Iturralde-Vinent*, 1994]. Correlation of this belt is difficult particularly from north to south across the domal structural high centered on the Los Organos belt (Figure 4). Moreover, our study has shown that in some cases marine sedimentary units of Paleocene and early Eocene age that are known to be coeval based on micropaleontological studies by *Bralower and Iturralde-Vinent* [1997] exhibit contrasting structural histories. For this reason, we refer to rocks of this belt using the general term of "overthrust plate" and by their geographic locality relative to the trace of the Pinar fault zone (Figure 2c): (1) the area of the overthrust Caribbean arc south of the Pinar fault zone (Los Palacios basin) and (2) area of the overthrust Caribbean north of the Pinar fault zone.

Previous Interpretations of Major Tectonic Phases in Western Cuba

Previous workers agree that most stratigraphic units of the underthrust plate of western Cuba were deposited during a protracted rift and passive margin phase lasting from the middle Jurassic to the Paleocene and that this passive margin phase was terminated by a major thrust event that affected western and central Cuba during early Tertiary time. Controversies involve the age and duration of this thrusting event and the nature of movement along postthrust faults such as the Pinar fault zone. We compare three of the more recent interpretations (Figure 3) of tectonic phases in western Cuba proposed by *Piotrowska* [1987], *Pszczólkowski and Flores* [1986], and our interpretation supported by biostratigraphic data presented by *Bralower and Iturralde-Vinent* [1997].

Prethrust and Early Thrusting Events

Piotrowska [1987] proposed that vertical uplift events of unknown origin and of Campanian and Maestrichtian age affected the western Cuba passive margin (Figure 3). *Pszczólkowski and Flores* [1986] proposed that hiatuses in Caribbean arc sections in central Cuba and the general lack of hiatuses and significant arc debris in passive margin rocks during the late Cretaceous and Paleocene supported the idea of a Late Cretaceous tectonic event that affected the Cuban arc but not the passive margin. *Hempton and Barros* [1993] proposed a long-lived and ongoing north verging thrust event that began in Campanian time and culminated in Eocene time. In their model, long-lived thrusting was envisioned to have progressed in an accretionary prism-type setting in front of the northeastward migrating Caribbean arc.

Thrusting Event

Age of deformation. C.W. Hatten (unpublished manuscript, 1957) proposed a middle Eocene age for thrusting in western Cuba based on the biostratigraphic age of the synthrust Manacas Formation which consists of highly sheared marine clastic rocks found as elongate belts along nearly all major thrusts in the Guaniguanico window (Figure 2b). This interpretation was later adopted by *Piotrowska* [1987] (Figure 3), although she also proposed a late stage south verging backthrusting event. In this paper we follow a synthrusting origin for the Manacas Formation but adopt its revised latest Paleocene/earliest Eocene age based on the recent and systematic micropaleontological study by *Bralower and Iturralde-Vinent* [1997] of faunas in the Manacas Formation. *Pszczólkowski and Flores* [1986] proposed that the termination of the thrusting event was marked by an unconformity separating the Capdevila and Punta Brava Formations of early Eocene age in the area to the north and east of the Pinar fault zone (Figure 3). Based on data presented in this paper, we propose that this unconformity dates the termination of strike-slip motion centered along the Pinar fault (our phases II and III) and that the main thrust event (our phase I) is post-Ancón Formation (early to late Paleocene) and coeval with the Manacas Formation of latest Paleocene/earliest Eocene age.

Differing tectonic models for thrusting. Two different models involving opposite directions of transport along the thrust faults of western Cuba have been presented. The first model consistent with the Caribbean plate reconstruction shown by *Pindell and Barrett* [1990] and *Mann et al.* [1995] involves the collision of a north facing arc with the passive margin of North America in the early Tertiary (Figure 5) (R. Graham, personal communication, 1991]. In this model, thrusting imbricates deep water, slope, and platform deposits of the passive margin. As a result of the northward thrusting, the island arc rocks, ophiolites, and the deepest water passive margin unit (the northern Rosario belt) are the structurally highest and farthest traveled units. The first appearance of arc detritus during Late Cretaceous time in the more distal passive margin units of the Northern Rosario belt supports the idea that this was the first passive margin unit to be influenced by the encroaching arc and therefore it is the thrust unit that was thrust the farthest [*Pszczólkowski*, 1994a].

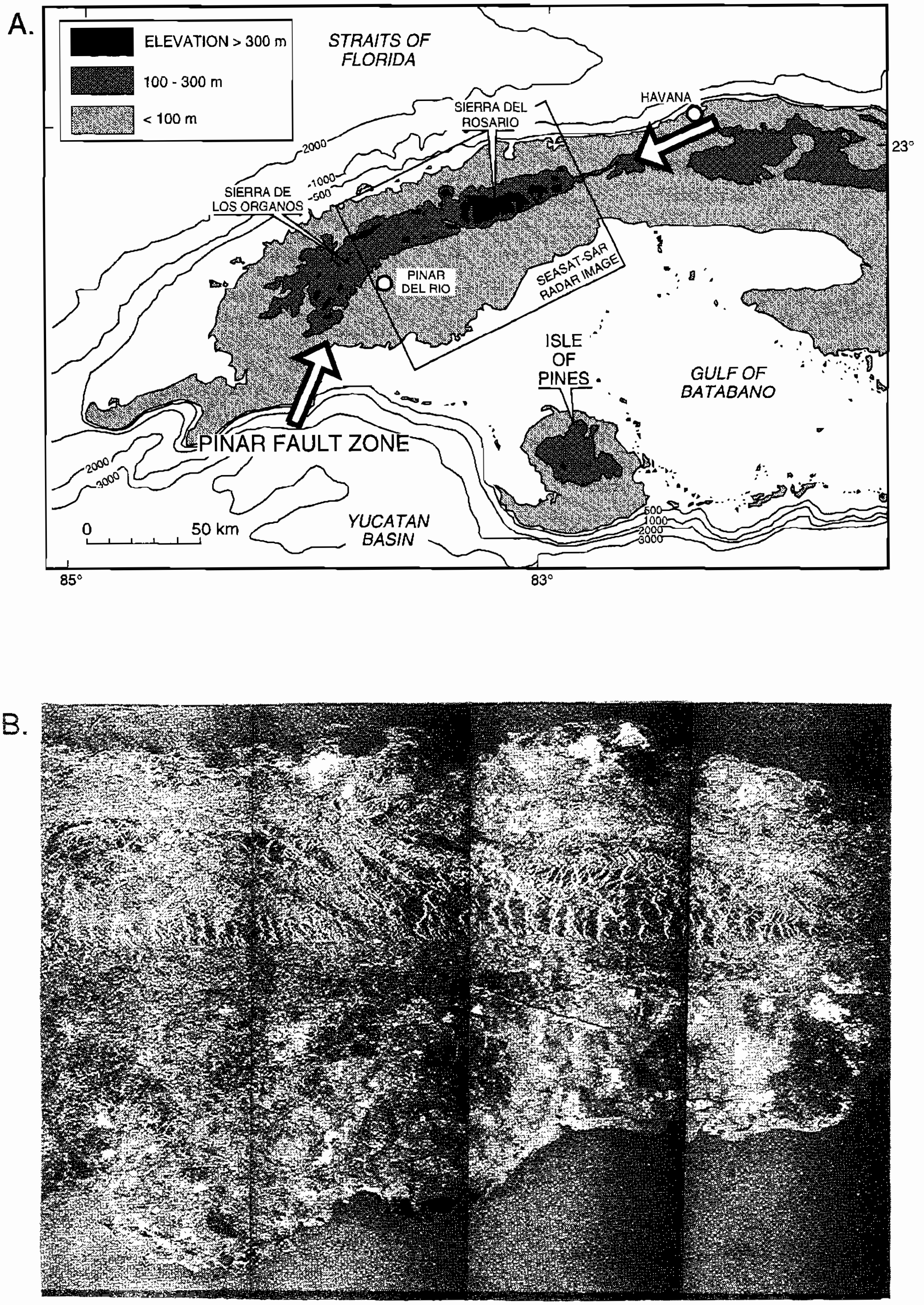

Figure 4. (a) Topographic map of western Cuba showing the relation of topography to the Pinar fault zone. (b) Seasat radar image of western Cuba. The linear Pinar fault zone makes an oblique angle with strike trends in Jurassic-Cretaceous units of the Sierra de Guaniguanico north of the fault. The topographically higher part of the Sierra de Guaniguanico in the northeast is the Sierra de Rosario, while the lower part to the southwest is the Sierra de los Organos.

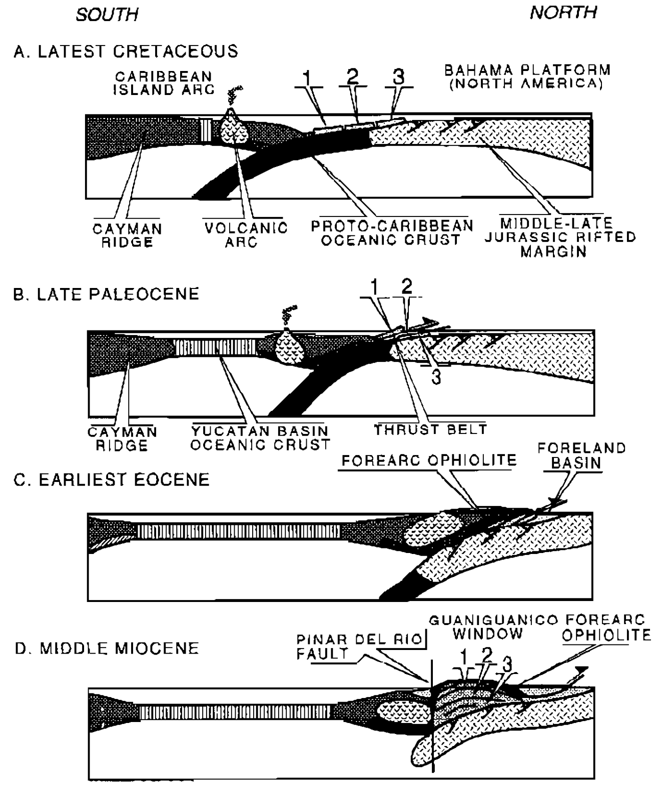

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Figure 5. Tectonic reconstructions of belts in western Cuba [*Pszczólkowski*, 1994a; R. Graham, personal communication, 1991]. (a) In Campanian time (84 Ma), the Caribbean arc is advancing to the northwest toward the North America passive margin (Bahamas carbonate platform and slope). The most distal and deepest water Lower Jurassic-Lower Cretaceous slope sediments crop out in the present day northern Rosario belt (1); the intermediate depth slope sediments crop out in the southern Rosario belt (2), and the most proximal, shallow-water platform rocks crop out in the Organos belt (3). The northeast facing Caribbean arc is active, but the Yucatan back-arc basin has not yet begun to open. (b) By late Paleocene (60 Ma), thrusting has begun to imbricate the passive margin rocks into thrust-bounded belts and passive margin sedimentation is terminated. Note that the farthest traveled and structurally highest sedimentary thrust slice (Northern Rosario belt) consists of the most distal and deepest water sedimentary rocks. Opening of the Yucatan basin accompanies the thrust phase. (c) During late Paleocene/early Eocene a forearc ophiolite is obducted on top of the thrusted margin sedimentary belts and remains the structurally highest thrust slice. (d) Left-lateral strike-slip faulting occurs along the Pinar fault zone during the latest early Eocene.

A second model [*Pushcharovskiy*, 1989; *Iturralde-Vinent*, 1994] proposes that a south facing Cuban subduction zone "chokes" on a piece of Caribbean continental crust now represented by continental basement presumed to underlie metasedimentary rocks exposed in windows of central Cuba (Figure 2a). Major differences between this model and the previous model summarized in Figure 5 are that it proposes north dipping subduction and the long-lived presence of an arc adjacent to the Bahamas Platform. Cuban ophiolites in the model of *Pushcharovskiy* [1989] and *Iturralde-Vinent* [1994] would have formed in a marginal basin setting adjacent to the Bahamas Platform and therefore the amount of ophiolite overthrusting would be much less.

Postthrusting Structural Events

Most agree that the linearity and topographic prominence of the Pinar fault zone (Figure 4) indicates that it has played an important, perhaps strike-slip, role in the tectonics of western Cuba. However, previous interpretations are not based on quantitative structural measurements and use little or no direct structural observations from exposures of the fault zone itself.

Early workers like *Rigassi-Studer* [1963] omitted the Pinar fault zone on their regional cross sections of the western Cuba fold-thrust belt. *Meyerhoff and Hatten* [1974] proposed that the fault is strike-slip and recently active. They extended the northeastern part of the fault northeastward into the Straits of Florida. *Pardo* [1975] proposed that the Pinar fault is a major Eocene thrust fault. *Piotrowska* [1978, 1987, 1993] proposed that the fault is a right-lateral strike-slip fault with large horizontal (160-180 km) and vertical (1.5-2 km) displacements and that the main phase of movement occurred between the middle Eocene and the Miocene. *Bresznyánski and Iturralde-Vinent* [1983] proposed that the fault is a left-lateral fault active from latest Eocene to middle Oligocene and a late Oligocene to Recent normal fault. *Rosencrantz* [1990] proposed that the fault is the left-lateral onshore extension of submarine faults forming the western margin of the Yucatan back-arc basin and was active during Paleogene overthrusting in Cuba.

Methods and Data Distribution

To delineate the tectonic evolution of western Cuba, we collected fault slip data from well-exposed sites, mostly quarries. The complete data set necessary for each fault (slickenside) plane includes fault orientation, orientation of slickenside lineation, and sense of slip. These data are then inverted for paleostress using the programs of *Angelier* [1979, 1984, 1990, 1991]. Only aspects of the techniques and programs used in this study are reviewed here.

Nature of Outcrops Studied

In order to do fault slip analysis, many fault planes with slickenside lineations must be collected at a relatively small site (preferably less than 10^4 m^2). Natural outcrop is normally insufficient for fault slip analysis because slickenside planes weather very quickly losing their lineations and making sense of slip more difficult to determine. The best outcrops for fault slip analysis tend to be large, active quarries. The sites used in this study, including several active quarries and many recently abandoned quarries, are shown in Figure 6. Excellent outcrops of clastic rocks of the Capdevila Formation were present at many dam spillways. In other locations, outcrops of these rocks were deeply weathered. We only found a few roadcuts and one railroad cut that exposed a significant density of faults necessary for the analysis. Several stream channels crossing the Pinar fault provided key outcrop that allowed us to constrain tectonic models even if we did not find a significant number of faults to do fault slip inversions.

Sense of Slip Criteria

Correctly determining the sense of slip on fault planes is an important first step in fault slip analysis and is more difficult than might be expected. Where obviously offset features such as bedding, dikes, or clasts are not available, other criteria must be found. Because carbonates form many of the outcrops in western Cuba, we were able to use the well-established techniques for these lithologies such as accretion steps (congruous steps) or stylolitic peaks (incongruous steps) [*Arthaud and*

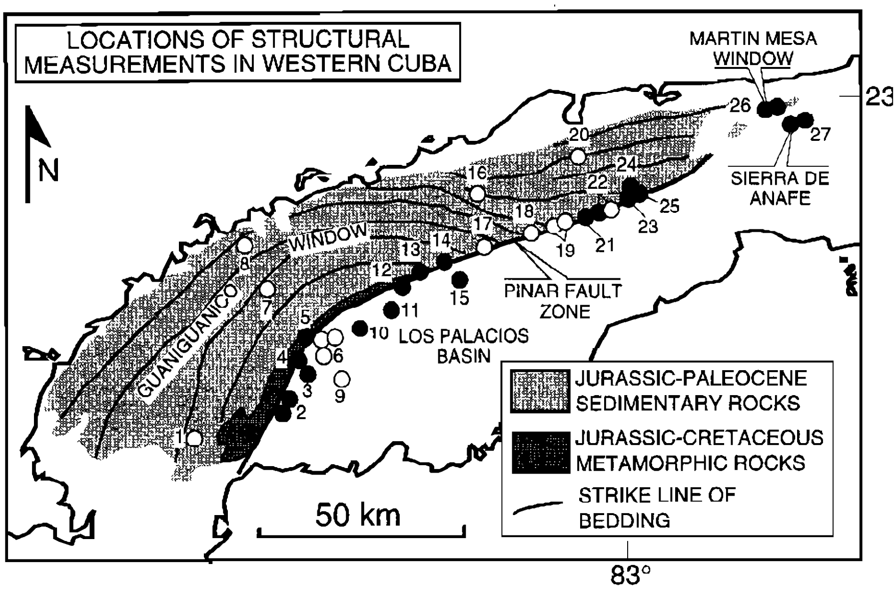

Figure 6. Map showing locations of sites where structural data were collected for this study. Numbers are keyed to the text, tables, and subsequent figures. Solid circles represent sites where data was analyzed and used in this paper. Open circles represent sites that were visited but did not have sufficient outcrop to warrant further study. Most quarries are located along the topographic scarp of the Pinar fault zone.

Mattauer, 1969; *Mattauer*, 1973; *Hancock*, 1985]. In addition, we found the RM criterion of *Petit* [1987] applicable to the sandstones of the Capdevila Formation.

Separation of Tectonic Phases

Different tectonic phases are identified during the course of fieldwork. Distinct tectonic phases are identified by searching for fault populations that contain conjugate faults. Normal, reverse and strike-slip faults are separated at this stage and oblique slip faults are plotted with the most compatible fault population [*Angelier*, 1989, 1994]. As more data are collected or after running the inversion program, the faults may be moved between sets or sets may be combined or individual faults may be removed from a population. In some cases, sets thought viable in the field are rejected after the computer analysis. During the computational work, a dominantly normal fault population may be combined with a dominantly strike-slip population and so forth. The end result is similar to initial estimates made during fieldwork. In some cases, major structures can be used to delineate tectonic phases. For example, our detailed mapping of exposed portions of the Pinar fault zone allowed us to identify sinistral faults parallel to the fault which were very likely to have formed during this tectonic episode. At the same location, we also identified dextral faults that are likely conjugate faults to the Pinar fault zone. The combined sinistral and dextral fault population defines one tectonic phase.

Relative Timing of Tectonic Phases

The sequence of tectonic events are determined by comparison of events present to the stratigraphic age and by analysis of overprinting relationships on and between fault planes. In western Cuba, the stratigraphy provides a very useful tool because a broad range of well-dated marine rocks is exposed (Figure 3). Thus Jurassic-Cretaceous age units should contain evidence of all tectonic phases, while middle Eocene and younger units should preserve only middle Eocene and younger deformation postdating arc collision (see Table 1). In order to better constrain these events, we collected samples for biostratigraphic analysis and age dating [*Bralower and Iturralde-Vinent*, 1997]. At each site, overprinting relations of slickenside lineations on individual faults (i.e., reactivated faults) and relations of crosscutting faults were noted. As the tectonic phases are separated, their sequence can be determined.

Data Output

Prior to inverting the fault data, a tectonic phase must be assigned to each fault. The phases are then inverted separately. In all cases, the inversion method INVD is chosen first [*Angelier*, 1979, 1984, 1990]. If this result is considered unreliable because of the presence of inherited faults (negligible friction), the method R4DT [*Angelier*, 1991] is used. When the analysis is complete, the stress directions and fault data as well as other relevant structural data are plotted. The symbols used on the plots are given in Figure 7.

The following output is generated by either inversion method (complete data given for each site in Tables 2-7): Axes of principal stresses σ_1, σ_2, and σ_3 ($\sigma_1 \geq \sigma_2 \geq \sigma_3$, compression positive), $\Phi = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$, ANG (the angle between observed slip (i.e., slickenside lineation) and the maximum resolved shear stress on the plane (as calculated from the σ_1, σ_2, σ_3 and Φ value given above)), and RUP (ratio upsilon defined by *Angelier* [1990]). Axes of principal stress are used for the tectonic analysis. The values of Φ, ANG, and RUP give one a basis for assessing the quality of the data and confirms or rejects the population as a single tectonic phase. Ideally, the Φ value should be about 0.5. ANG and RUP [*Angelier*, 1990] are two distinct methods of showing the deviation between the observed fault slip and the computed shear stress on the fault

Table 1. Microtectonic Data Summary

Site Location	Site Name	Formation	Formation Age	Tectonic Phases					
				I. NW-SE Compression	II. NNE-SSW Compression	III. ENE-WSW Compression	IV. ESE-WNW Tension	IV. N-S Tension	V. NW-SE Compression
2	Lagunilla	San Juan y Martinez	Late Cretaceous	313					
	Junta Macurijes	Capdevila	Early Eocene			067			
	Combined			314		068	115		
3	Río Feo	Capdevila	Early Eocene			055 (J)	110 (J)	010 (J)	
4	El Rancho	Capdevila	Early Eocene		035 (J)		100 (J)	355 (J)	
5	Mestanzas North	Jagua and Guasasa	Jurassic-Cretaceous		006		256		
	Mestanzas South	Jagua and Guasasa	Jurassic-Cretaceous		027		277		
	combined				004		291	194	
10	Río Paso Viejo	Capdevila	Early Eocene		192		110	173	
11	Río Hondo	Capdevila	Early Eocene				100 (J)	360 (J)	130 (J)
12	Río Juan Morano	Cangre and Capdevila	Jurassic and Early Eocene		025 (R&J)				
13	Sitio Peña	Guasasa	Jurassic-Cretaceous	335	006	259	072	167	106
14	Rigo Fuentes	Guasasa	Jurassic-Cretaceous		210		073	323	
15	Entronque de Herradura	Loma Candela	Middle Eocene				095	159	
21	La Reforma	Artemisa	Jurassic-Cretaceous		226		275	143	
22	La Muralla	Artemisa	Jurassic-Cretaceous	359	042	097	098	156	320
23	La Manuelita	Serpentinite and Artemisa	Jurassic-Cretaceous		200			219	
24	Soroa	Atemisa	Jurassic	167				184	
25	Pedestal	Artemisa	Jurassic	168	032				
26	Railroad tracks	Polier	Cretaceous		021				
	La Vega	Artemisa and Polier	Jurassic-Cretaceous		017			162	289
	combined				019			162	287
27	de la Cruz	Husillo	Early Miocene				127	170	292
	Domingo Fernandez	Husillo	Early Miocene				129		
	combined						124	170	292

List of sites, names, geology and phases present. Roman Numerals are keyed to maps that follow for each phase.

Where stress directions were determined by joints only (no faults or too few faults) a J is indicated in parentheses. Where stress directions were determined by Riedel shear geometries, an R is given in parantheses.

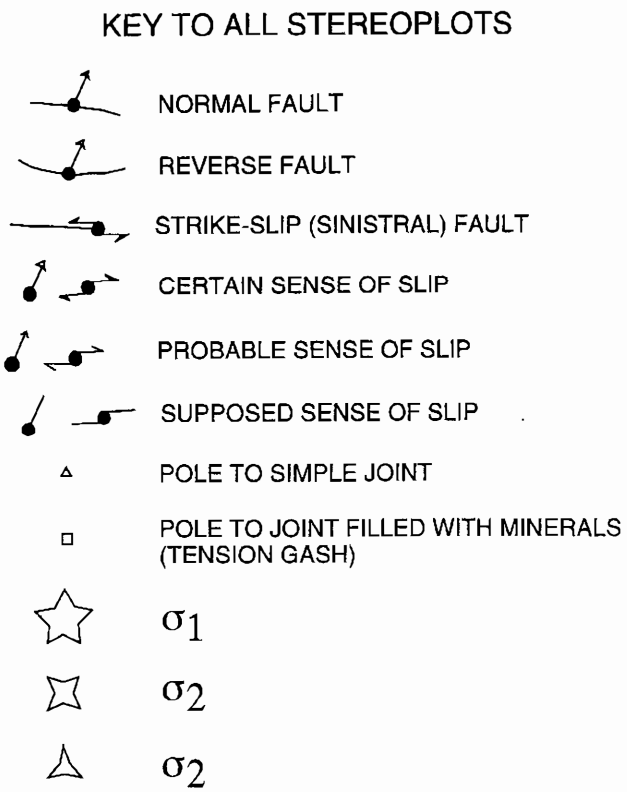

Figure 7. Key to plots of structural data.

plane. ANG is given in degrees (0-180°); RUP in percent (0-200%). A value of ANG less than 10° is very good as is a value of RUP less than 15%. Values of ANG and RUP are given for each fault plane. If the values for an individual fault are greater than 25° for ANG and/or 50% for RUP, the fault is normally excluded from the population. Faults with high values of RUP and ANG are not considered to have formed under the same tectonic stress as the rest of the population [*Angelier*, 1994]. In Tables 2-7, we include only the mean values of ANG and RUP for the population.

Distribution of Sites

Several criteria were used to select sites for detailed fault study. First, we selected locations with excellent outcrop. In general, these were quarries or dam spillways. Second, we sought outcrops with a range in ages from Jurassic to early Miocene. Finally, we concentrated on the Pinar fault zone because elucidating its history was a major goal. We placed more emphasis on studying rocks of synthrusting to postthrusting age because the older rocks have experienced more tectonic phases, are more folded, and thus yield less information concerning the latest tectonic events. It is difficult to restore the faults at some sites to their orientation at the time of their formation because the folding is too complex. Thus we were not able analyze the early phase I faults at many sites. The outcrops that we studied of Capdevila and younger rocks generally have dips less than 20°. Some exceptional higher dip areas were studied, such as site 12 at the Rio Juan Morano, where dips greater than 40° are related to the proximity of these rocks to the Pinar fault zone. The stratigraphic age of each site is given with the principal orientations (compression or tension) of the phases present in Table 1.

Phase I: Paleocene Thrusting

Numerous large offset thrust faults formed during the Paleocene/early Eocene arc/continent collision in western Cuba [*Piotrowska*, 1987, C.W. Hatten, unpublished report, 1957]. The principal tectonic units such as the Late Cretaceous island arc, the ophiolitic rocks, the Sierra del Rosario, and the Sierra de los Organos were imbricated and thrust over each other. The timing of the thrusting is given by the age of the synorogenic Manacas Formation, latest Paleocene to early Eocene (nannofossil zones NP9 through NP13) [*Bralower and Iturralde-Vinent*, 1997]. The Capdevila Formation may have been involved in the deformation [*Bralower and Iturralde-Vinent*, 1997]. However, our study did not reveal thrust fault populations in the Capdevila Formation probably because we sampled only the younger part of the Capdevila Formation (NP11-NP12) [*Bralower and Iturralde-Vinent*, 1997], exposed south of the Pinar fault.

Complex folding of both the rocks and the faults probably related to the collision makes inversion of the data difficult. A few sites were less complexly folded and could be analyzed either without rotating the data or by rotating the entire data set. The data from site 13 (Sitio Peña) were restored to paleohorizontal by a 25° rotation. The data from this site and four others show a phase of NW-SE to N-S compression resulted from slip on generally NE-striking reverse faults (Figure 8). Generally, σ_1 and σ_2 are approximately horizontal and σ_3 is approximately vertical (Table 2), as expected for thrust-faulted terrains. At some sites σ_3 and σ_2 are reversed because they are dominated by strike-slip faults. These strike-slip faults may have formed during thrusting as a result of the same compression as the major thrusts. The quality of the data as indicated by Φ, ANG, and RUP (Table 2) is mostly good except for site 25 which is marginal.

The NW-SE to N-S compression is nearly perpendicular to the Pinar fault at most locations. This compression is compatible with thrust or reverse movement along the fault during this tectonic phase. Generally, the later sinistral structures completely overprint any preexisting faults within the principal fault zone. However, in the Soroa region (sites 23 and 25 and adjacent exposures), the fault zone, exhumed by quarrying, preserves evidence of high-angle reverse faulting. At these localities, the reverse faults are overprinted by sinistral faults but not obliterated. Thus the Pinar fault could have been a reverse fault during this deformation and later reactivated as a sinistral fault.

The vergence of the thrust belt cannot be addressed from the fault slip data alone. C.W. Hatten (unpublished report, 1957) proposed north directed thrusting based on the orientation of fold axes near the thrust zones. On the other hand, *Piotrowska* [1978] accepted that the Sierra de los Organos experienced north directed overthrusting, but proposed that the Bahía Honda allochthon was emplaced from north to south [*Piotrowska*, 1993]. Detailed mapping (Figure 9) of the La Reforma Quarry (site 21) shows south dipping axial planes and thus probably a northward vergence, although we could not prove it due to the absence of bedding top indicators. North directed thrusting was proven in an outcrop of San Cayetano Formation (Figure 10), in agreement with C.W. Hatten (unpublished report, 1957). The downward facing folds are similar in style and orientation to folds illustrated by *Piotrowska* [1987] throughout western Cuba, although she did not note their younging directions. If the downward facing folds are consistent, the direction of thrusting is southeast to northwest for all allochthons in western Cuba.

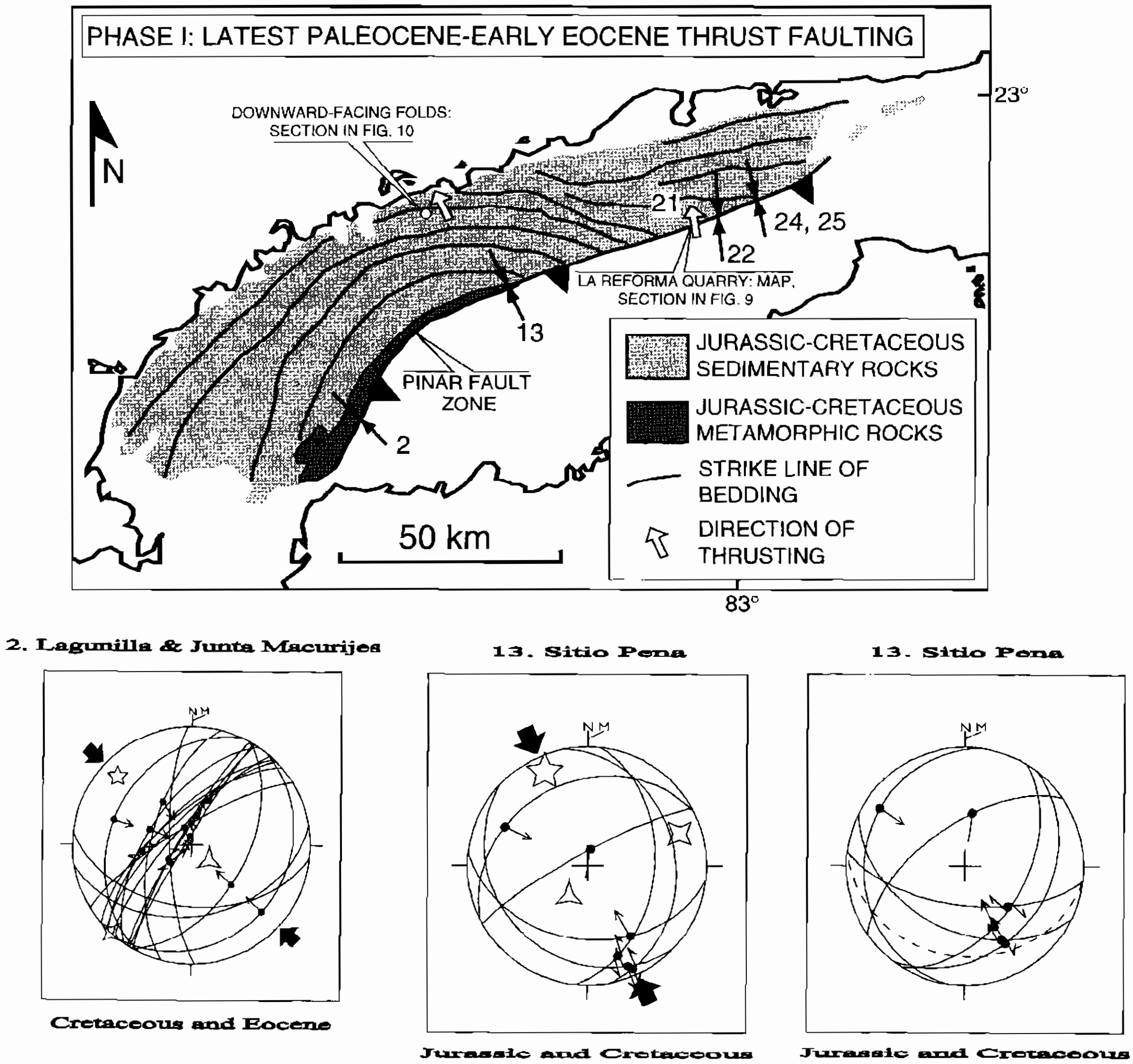

Figure 8. Map shows strike lines of bedding and foliations in Sierra de Guaniguanico, four sites studied along the Pinar fault zone and two localities where overturned folds were used to determine the direction of overthrusting in rocks of Jurassic and Cretaceous age (solid arrows indicate direction of maximum compression as derived from the fault plots shown; open arrows indicate sites shown in Figures 9 and 10 where a northward vergence direction was documented). The NW-SE to NNW-SSE compression determined from the fault slip data in Jurassic-Cretaceous rocks is not present in the early Eocene Capdevila Formation and younger rocks and therefore occurred in pre-early Eocene time. This compression direction is consistent with the general trends of bedding and foliations and the NW trending lineation data [*Piotrowska*, 1993].

Table 2. Phase I (NW-SE Compression) Results of Fault Slip Inversion

Site	Site Name	σ_1	σ_2	σ_3	Number of Faults	Φ Value	ANG, deg	RUP, %
2	Lagunilla	313 16	222 01	130 74	11	0.75	14	37
	Junta Macurijes							
	Combined	314 16	223 00	132 74	12	0.75	13	34
13	Sitio Peña	335 14	071 19	211 66	06	0.32	08	33
22	La Muralla	359 23	182 67	090 01	13	0.36	13	29
24	Soroa Quarry	167 10	359 80	258 02	09	0.27	11	32
25	Pedestal	168 22	260 04	001 67	04	0.84	20	45

Axes of principal stresses, number of faults used in inversion program, Φ value, ANG, and RUP of Phase I (NW-SE compression) at individual sites.

$\Phi = (\sigma_2-\sigma_3)/(\sigma_1-\sigma_3)$. ANG is the average angle between predicted and observed shear [*Angelier*, 1979]. RUP is the ratio upsilon (defined by *Angelier* [1990]).

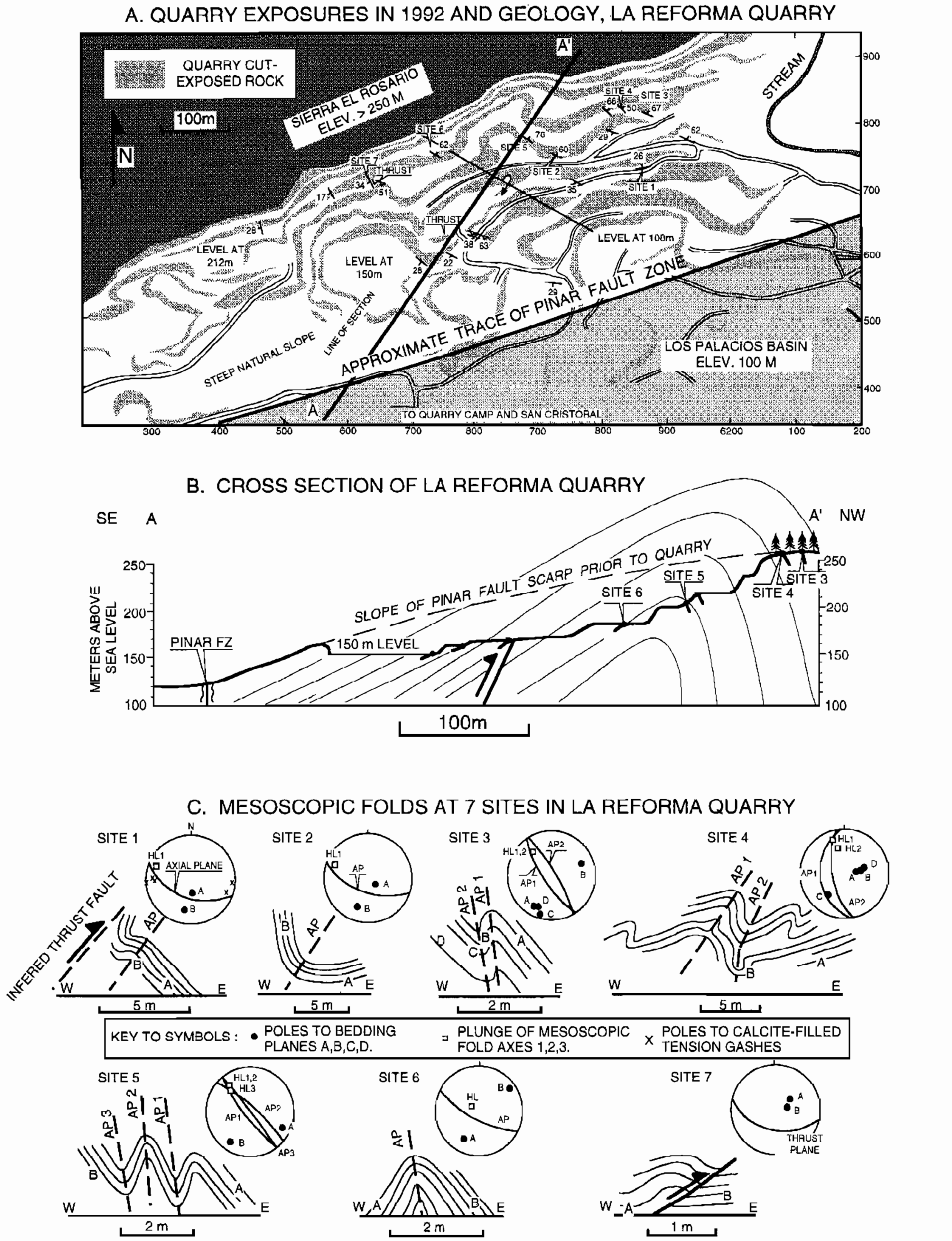

Figure 9. (a) Map of quarry exposures in 1992 and structure at La Reforma quarry on the scarp of the Pinar fault zone (see Figure 8 for location). The exposed lithology is Artemisa Formation of Late Jurassic-Early Cretaceous age. (b) Cross section of La Reforma quarry showing large overturned, northeast verging fold in the Artemisa Formation. This strike trend forms the lineaments seen in the Sierra del Rosario on the radar image in Figure 4. Sites along the line of section where mesoscopic fold data were collected are indicated and shown in Figure 9c. (c) Mesoscopic fold data from La Reforma quarry.

Phase II: Post-Early Eocene Compression I

A regionally important N-S to NE-SW compression affected most of the sites studied. This compression occurs in rocks of early Eocene age and older (Table 1) but not in the upper middle Eocene and younger rocks. Thus the deformation occurred after and/or during the deposition of Capdevila Formation and prior to deposition of the Loma Candela Formation (Figure 3). The age of Capdevila Formation at the sites studied is early Eocene (nannofossil zones NP11-12) [*Bralower and Iturralde-Vinent*, 1997]), and the age of the Loma Candela Formation is middle Eocene (NP zone 15) [*Bralower and Iturralde-Vinent*, 1997]) at Entronque de Herradura (site 15), the only site studied of this formation.

Generally, the sites do not appear to have experienced significant rotation during or after this deformation. However, a 25° rotation to restore paleohorizontal yields a more likely fault configuration at Sitio Peña (site 13) (Figure 11). Prior to restoration, most of the slickenside lineations plunge to the south, and several are parallel to the bedding plane. After rotation, these lineations are horizontal, and the southward bias in the lineation data set as a whole is removed. Another site with significant tilting occurs within the Pinar fault zone in Río Juan Morano (site 12), but the measured faults appear to have formed after the bedding tilt was established.

Inversion of fault data from sites in Jurassic-Cretaceous rocks north of the fault and from sites in the Capdevila Formation south of the fault yields N-S to NE-SW compression (Figure 11). A few NW striking reverse faults are compatible with the N-S to NE-SW compression (Figure 11) but not the earlier NW-SE compression that was dominated by reverse faults. The inversions yield horizontal σ_1 and σ_3 orientations and vertical σ_2 orientations (Table 3) because of the dominance of strike-slip faults. The Φ values are generally in the range 0.3 to 0.5 (Table 3) which demonstrates that the data sets are internally compatible. The values of ANG and RUP are generally low and are all within the acceptable range (Table 3).

The N-S to NE-SW compression occurs at a low to moderate angle to the Pinar fault zone (Figure 11). These directions are completely consistent with sinistral shear along the fault. However, without supporting data, they do not prove that the fault underwent sinistral shear nor that the stress directions occurred at the same time as major fault movement. By detailed mapping of sites along the fault, we found that some of these sites are tectonic slivers emplaced along the fault (Figure 12). Slivers such as these are common features of strike-slip faults but, in this case, do not indicate the sense of slip.

We also conducted detailed mapping of exposed sections of the Pinar fault zone in order to constrain the sense of slip on the fault. The best exposed sections are along Río Juan Morano (site 12) and Río Santa Cruz (west of site 21). Other areas have been exposed by quarrying and include an area north of site 22, site 23 and site 25 (Figure 6; Table 1). The Pinar fault places early Eocene Capdevila Formation [*Bralower and Iturralde-Vinent*, 1997] against Cangre metamorphic rocks [*Pszczólkowski*, 1985] in the Río Juan Morano (Figure 13a). The most sheared metamorphic rocks occur directly underneath the road bridge and are on strike with the topographic break that defines the Pinar fault zone. The limestone underneath the bridge and the limestone blocks within the schist to the north have a well-developed SC fabric that displays sinistral shearing. To the south of the bridge, the Capdevila Formation is cut by numerous sinistral faults parallel to the Pinar fault and by

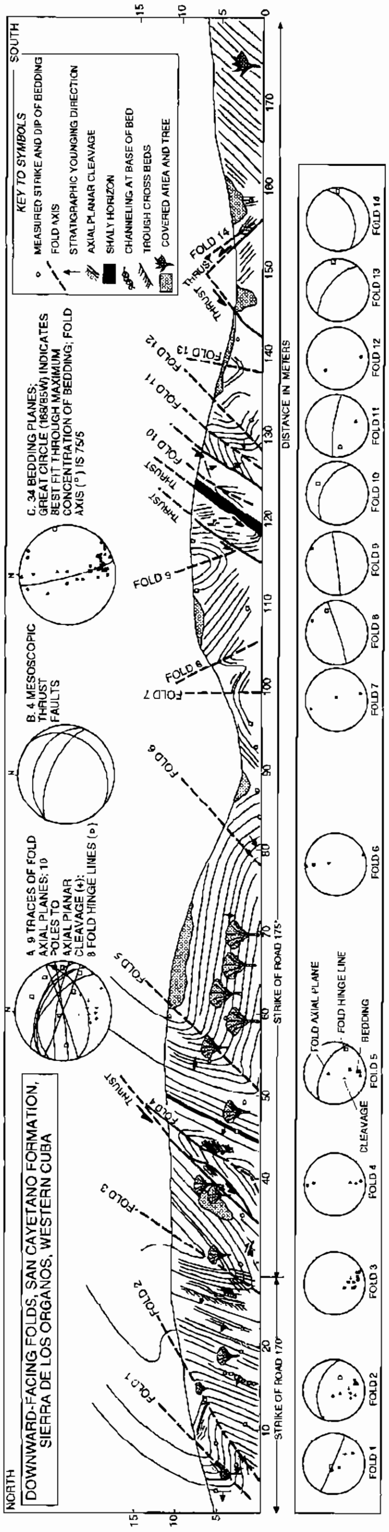

Figure 10. Cross section of road outcrop of downward facing folds in the San Cayetano Formation in the Sierra de los Organos (see Figure 8 for location). Direction up indicators (sole marks) are shown by small arrows. Plots give attitudes of folds. The facing direction of all folds suggests northward tectonic transport consistent with the schematic tectonic model favored in this paper and summarized in Figure 5.

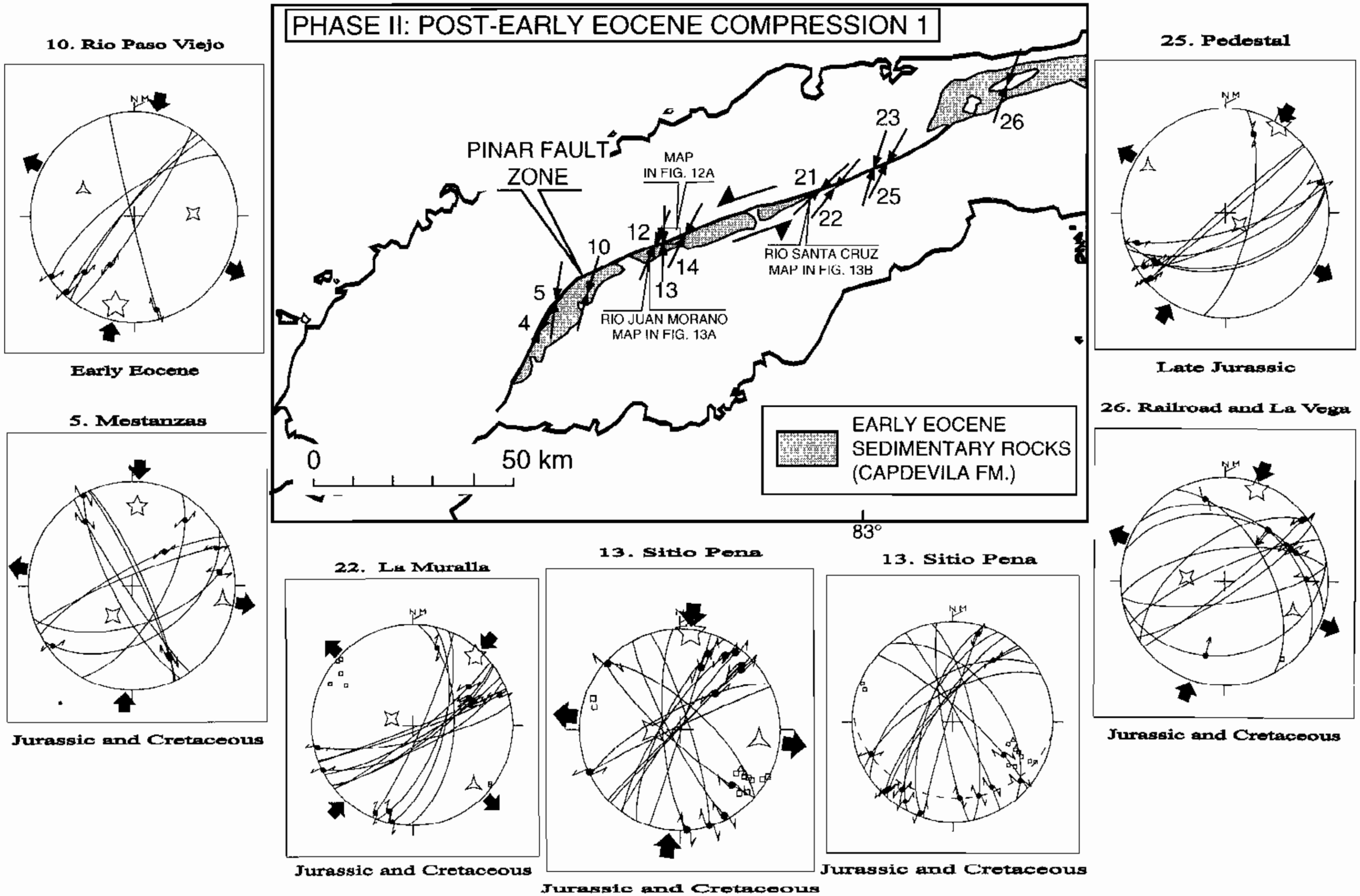

Figure 11. Map showing the sites where phase II was found (arrows indicate direction of maximum compression as derived from the fault plots shown). This was the first phase that affected lower Eocene rocks of the Capdevila Formation. The data from site 13 (Sitio Peña) were restored to paleohorizontal defined by the bedding plane shown (dashed great circle) in the unrotated data set. Compression directions vary from about 010 to 040. These directions as well as mesoscopic field data from the fault zone indicate that this compression occurred during sinistral shear along the Pinar fault zone. The rotation of stress direction from phase I compression may represent the change to more easterly motion of the Caribbean plate following the arc/continent collision.

Table 3. Phase II (NNE-SSW Compression) Results of Fault Slip Inversion

Site	Site Name	σ_1	σ_2	σ_3	Number of Faults	Φ Value	ANG, deg	RUP, %
5	Mestanzas North	006 23	236 57	106 23	05	0.49	15	41
	Mestanzas South	027 14	118 06	233 75	04	0.23	12	30
	combined	004 25	213 62	099 12	09	0.49	16	35
10	Río Paso Viejo	192 16	088 42	298 44	05	0.17	10	35
13	Sitio Peña	006 03	269 68	097 22	13	0.39	10	31
14	Rigo Fuentes	210 01	102 87	300 03	06	0.44	07	26
21	La Reforma	226 02	323 77	135 13	04	0.44	04	31
22	La Muralla	042 07	289 72	134 16	12	0.31	13	43
23	La Manuelita	200 18	307 43	094 42	05	0.46	12	44
25	Pedestal	032 02	128 76	301 14	08	0.22	09	31
26	Railroad tracks	021 06	288 27	123 62	05	0.24	05	23
	La Vega	017 15	244 69	111 15	05	0.41	08	29
	combined	019 08	276 60	113 29	10	0.29	11	32

Riedel shears. Thus the sinistral shearing occurred after the deposition of this unit in the early Eocene [*Bralower and Iturralde-Vinent*, 1997].

Artemisa Formation is faulted against the Capdevila Formation in the Río Santa Cruz (Figure 13b). The Artemisa Formation is coherently bedded north of the topographic scarp but highly sheared on strike with the scarp. The SC fabric developed in the fault zone also indicates a sinistral sense of shear. The occurrence of sinistral faults within the Pinar fault zone during the early Eocene links the sinistral movement on the Pinar fault to the mesoscopic fault data sets with NE-SW compression found at Sitio Peña and other sites.

Phase III: Post-Early Eocene Compression II

Faults associated with an ENE-WSW to E-W compression (Figure 14) overprint faults associated with the N-S to NE-SW compression. This compression occurs in the same age units as the N-S to NE-SW compression; thus it is a slightly younger deformation but still pre-Loma Candela (late middle Eocene in age). The σ_1 and σ_3 axes are horizontal, and the σ_2 axes are vertical (Table 4) as is typically the case with strike-slip data sets. Only the Φ value at site 13 is close to 0.5; the other Φ values are relatively high (Table 4). The stress directions are reliable at sites 2 and 13. The principal stress axes are approximate at La Muralla (site 22). The ANG and RUP at sites 2 and 13 are low and within the acceptable range at site 22 (Table 4). All sites are dominated by reactivated faults.

To the best of our knowledge, no major structures formed in western Cuba during this event. Also our detailed mapping of the Pinar fault zone did not reveal a dextral reactivation of the principal fault zone. The data show that σ_1 developed a more easterly orientation in response to changing tectonic conditions after the principal phase of activity on the Pinar fault. We propose that this is due to postcollision reorganization of the tectonic regime in the northern Caribbean region as the collision migrated to the east.

Phase IV: Post-Early Miocene Tension

Normal faults are ubiquitous in western Cuba and occur in Jurassic to Miocene age rocks. Where the rocks are older than Miocene in age, we assume that the normal faults are contemporaneous with the Miocene deformation because the normal faults are consistently the late formed faults. Only strike-slip faults associated with phase V overprint the normal faults.

The deformation is documented not only by the fault slip analysis but also by the presence of outcrop scale faults, rollover anticlines and associated jointing that are documented here as well as on previously unpublished quarry maps reproduced here. Two directions of tension are commonly found at most outcrops. One is N-S and apparently was more dominant because of the greater abundance of E-W major normal faults. The other is ESE-WNW. Neither set of faults consistently overprints the other nor could any variation in the timing be observed by stratigraphic position of the affected rocks. Thus the two directions were contemporaneous to the limit of our observation, but we will discuss them separately below.

The effect of N-S tension is more commonly observed than that of the ESE-WNW one. Although the fault orientations vary, consistent N-S σ_3 orientations occur because the slickenside lineations trend north or south (Table 5 and Figure 15). The fault slip inversions also show that σ_1 orientations are vertical or steeply plunging, as expected for normal faulting. Likewise, the σ_2 and σ_3 orientations are horizontal or have low plunges (Table 5). Most Φ values are in the range or 0.34 to 0.53 which are excellent and the others are acceptable (Table 5). The values of ANG and RUP are uniformly low. These results show that the data are very robust for this tectonic phase.

An ESE-WNW tension is also present. As with the N-S tension, σ_1 orientations are vertical or steeply plunging, and σ_3 and σ_2 have low plunges (Table 6). Most Φ values occur in the range from 0.30 to 0.58 (Table 6), indicating highly compatible data. The values for ANG and RUP are generally low (Table 6). As with the N-S tension, the results of the fault slip analysis are excellent for this phase.

The post-early Miocene extension in western Cuba is not only expressed in the mesoscopic fault data but is also expressed by geologic map relationships and the physiography. Geologic mapping of the lower Miocene and younger rocks in the Sierra de Anafe shows abundant evidence of E-W normal faults (Figure 16). Normal faults appear on the aerial photographs of the region (Figure 16b). The middle Miocene Guines and Cojimar Formations have bedding plane dip values of 5-20° [*de Albear-Fránquiz and Iturralde-Vinent*, 1985] which probably developed during the post-early Miocene extension. Although we do not have mesoscopic fault data from these

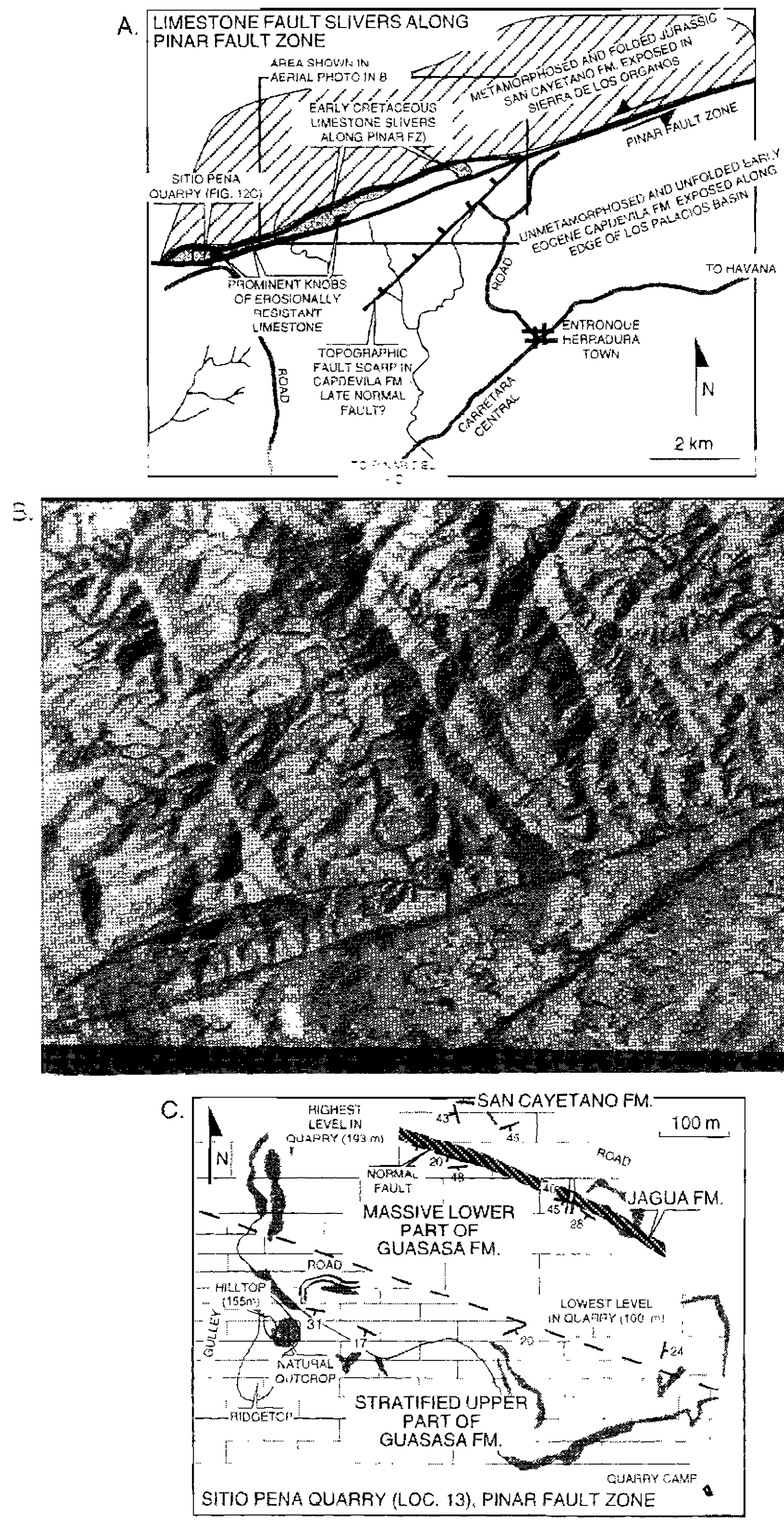

Figure 12a. Map of Upper Jurassic-Lower Cretaceous limestone slivers along the Pinar fault zone near the Sitio Peña and Rigo Fuentes quarries (sites 13 and 14, respectively). Limestone slivers were generated by strike-slip motion along the Pinar fault zone in phase II and juxtapose Middle Jurassic San Cayetano Formation north of the fault in the Sierra de los Organos with Eocene Capdevila Formation south of the fault in the Los Palacios basin. The smaller scarp extending to the southwest in rocks of the Capdevila Formation may be related to later normal faulting; if normal, its orientation would be consistent with its origin during phase II left-lateral slip on the Pinar fault zone.

Figure 12b. Detail of aerial photograph showing scarp of Pinar fault zone and subsidiary normal (?) fault splay affecting early Eocene rocks of the Capdevila Formation. Normal throw on the subsidiary fault is consistent with coeval left-lateral offset on the Pinar fault zone. (c) Detailed map of Sitio Peña quarry along Pinar fault zone (see Figure 12a for location; site 13 in Figure 8).

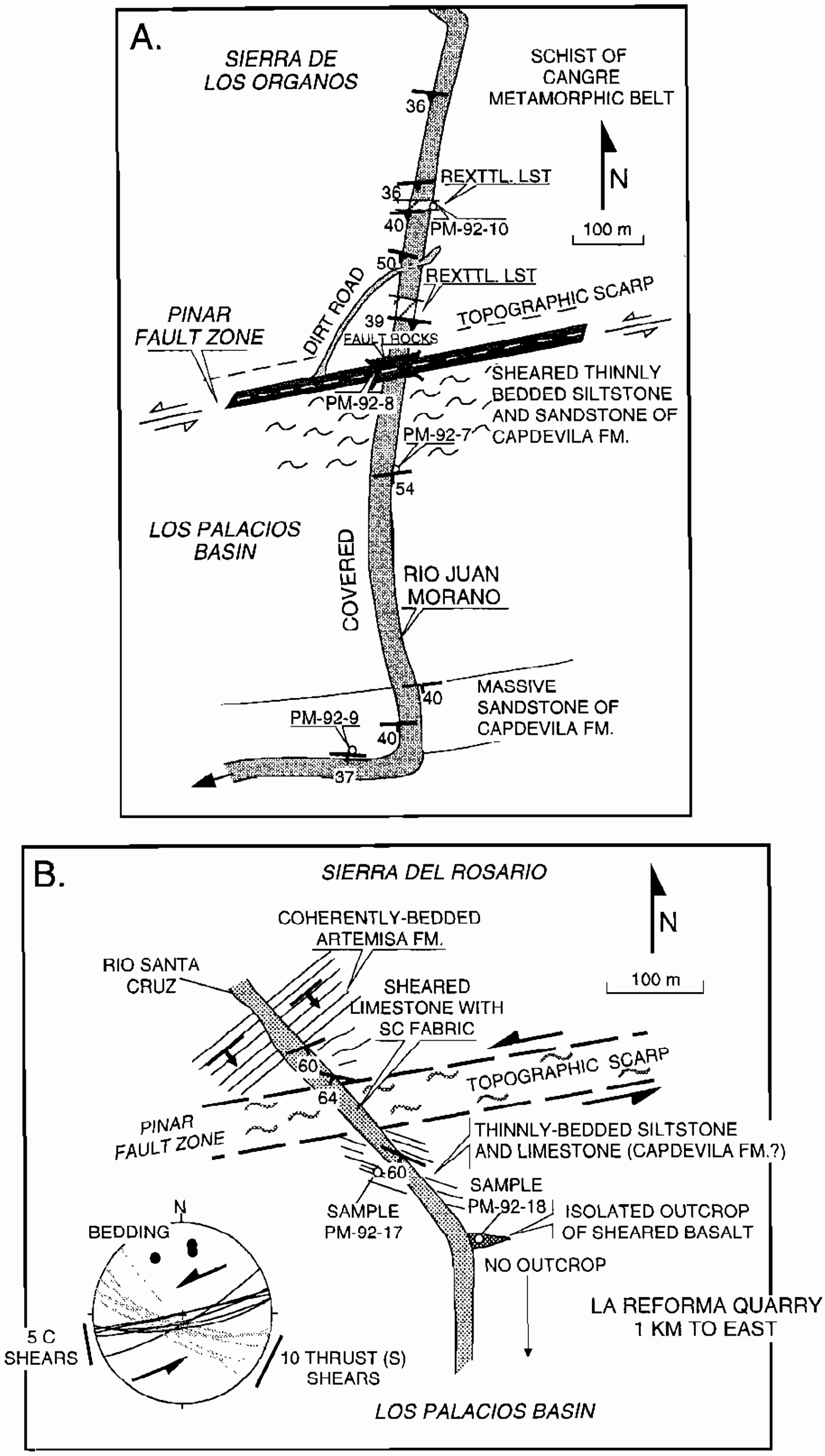

Figure 13. (a) Map of Pinar fault zone in Rio Juan Morano (site 12, see Figure 11 for location). Sample PM-92-7 and other samples from the Capdevila Formation yielded early Eocene microfauna and constrains the age of left-lateral shearing along the Pinar fault zone to be post-early Eocene. (b) Map of Pinar fault zone in Rio Santa Cruz (west end of site 21; see Figure 11 for location). Inset shows orientation of SC structures consistent with left-lateral shear along the fault inferred from measurements taken outside of the actual fault zone.

younger formations, the mapped features suggest that the extension continued or even started in the middle Miocene, slightly later than the deposition of the rocks exposed in the Sierra de Anafe. Quarry geologists have mapped normal faults in the quarries (Figures 16c and 16d) and throughout the range. The E-W faults are more continuous and have larger throws, suggesting that the N-S extension was the more important of the two. Rollover anticlines are associated with some of the

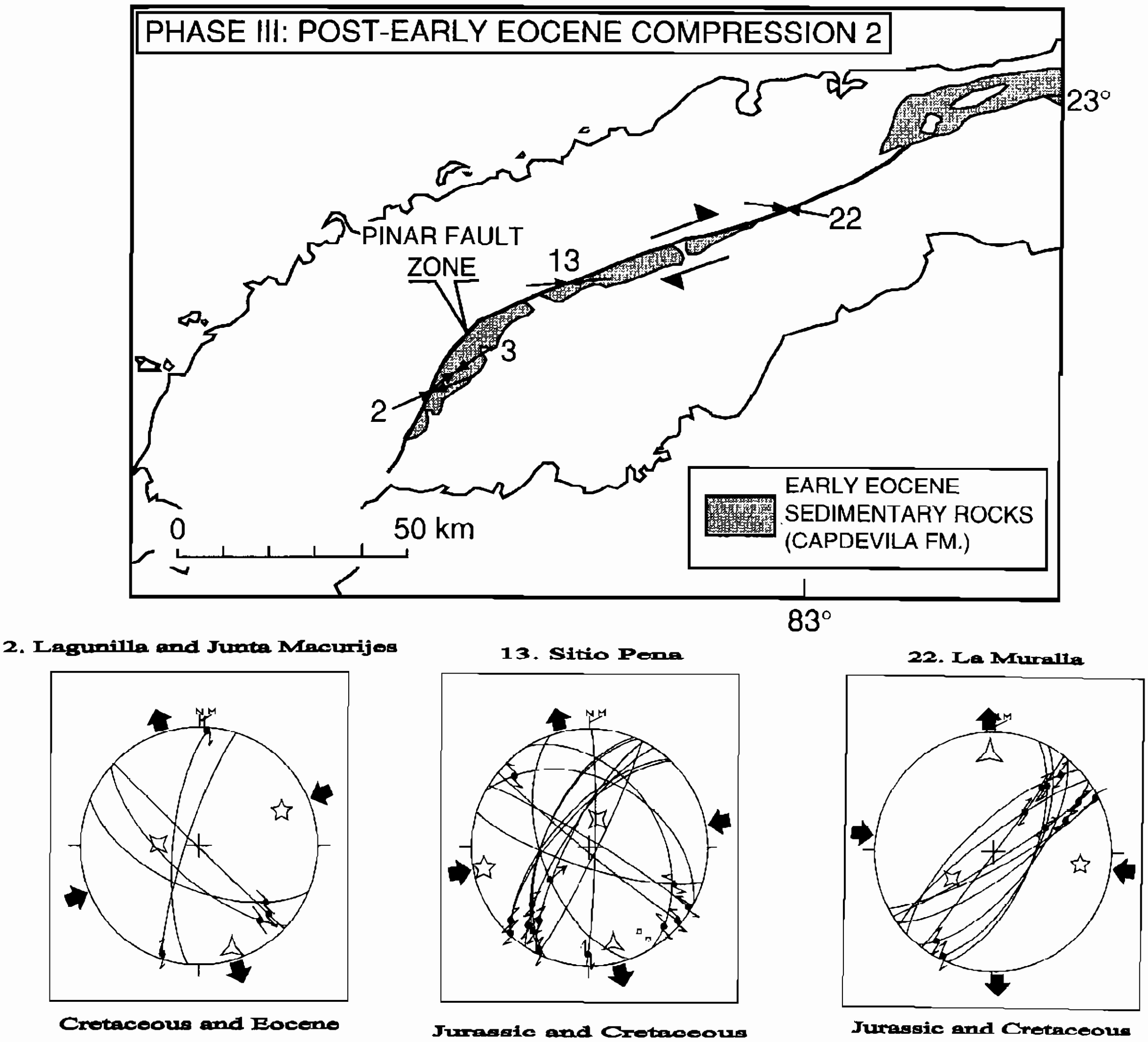

Figure 14. Map showing the sites where phase III was found (arrows indicate direction of maximum compression as derived from the fault plots shown). This was the second phase that affected lower Eocene rocks of the Capdevila Formation. The rotation of stress direction from phase II may represent the change to more easterly motion of the Caribbean plate following the arc/continent collision.

larger mapped faults (Figure 17) suggesting that the faults are listric at depth. The outcrop scale faults mapped by the quarry geologists are parallel to the mesoscopic faults used in the fault slip analysis. Both the outcrop scale and the mesoscopic normal faults therefore formed under the same N-S tension.

The post early Miocene extension also appears to be expressed in the topography of western Cuba. The range pattern of western Cuba is not particularly reminiscent of a fold-thrust belt. Instead, the region is dominated by linear narrow ranges with abrupt range fronts. For example, in the Sierra de Ancón region, geologic mapping [*Pszczólkowski et al.*, 1987, and C.W. Hatten, unpublished report, 1957] shows repeated section and the presence of Eocene mélange rocks (Manacas Formation), yet the topographic breaks are more abrupt than might be expected from the thrusting (Figure 18). These range fronts appear to be formed by normal faults.

Previous models of the Caribbean tectonic evolution [e.g., *Pindell and Barrett*, 1990] did not predict this tectonic phase.

Table 4. Phase III (ENE-WSW Compression) Results of Fault Slip Inversion

Site	Site Name	σ_1	σ_2	σ_3	Number of Faults	Φ Value	ANG, deg	RUP, %
2	Lagunilla							
	Junta Macurijes	067 20	272 62	162 10	04	0.77	04	23
	combined	068 24	278 63	163 12	05	0.79	04	21
13	Sitio Peña	259 10	017 70	166 17	14	0.51	08	24
22	La Muralla	097 27	236 56	357 19	10	0.88	18	33

Table 5. Phase IV (N-S Tension) Results of Fault Slip Inversion

Site	Site Name	σ_1	σ_2	σ_3	Number of Faults	Φ Value	ANG, deg	RUP, %
5	Mestanzas North Mestanzas South combined	345 75	102 07	194 14	04	0.20	05	21
10	Río Paso Viejo	299 66	078 19	173 15	09	0.53	02	16
13	Sitio Peña	024 71	260 11	167 15	09	0.26	08	25
14	Rigo Fuentes	060 76	233 14	323 02	09	0.28	07	20
15	Entronque de Herradura	000 75	250 05	159 14	14	0.34	09	34
21	La Reforma	043 84	233 06	143 01	09	0.43	05	17
22	La Muralla	295 73	063 11	156 13	08	0.26	11	27
23	La Manuelita	001 73	126 10	219 13	04	0.51	10	32
24	Soroa	303 67	090 19	184 12	10	0.36	08	24
26	Railroad tracks							
	La Vega	067 82	252 08	162 01	07	0.45	08	24
	combined	048 81	253 08	162 04	09	0.47	06	25
27	de la Cruz	030 87	260 02	170 02	19	0.34	09	27
	Domingo Fernandez combined	028 87	260 02	170 02	20	0.34	09	25

Western Cuba was assumed to be tectonically quiescent during the Miocene. However, its ubiquitous nature, its apparent effect on the topography and the mesoscale structures observed in the Sierra de Anafe suggest that the phase is a principal element of tectonic development of western Cuba. Late orogenic extension is observed in many mountain belts and is generally attributed to gravitational collapse due to high topography and thickened crust [*Malavieille and Seranne*, 1996]. However, the normal faulting occurred in western Cuba 30 m.y. after the island arc/continent collision. As in many mountain belts, the thrusting and even some of the postthrusting activity occurred while Cuba was still submerged as demonstrated by the presence of marine sedimentary rocks in front of the thrust sheets (i.e., Manacas Formation) and in postthrusting rocks (Capdevila Formation) and even in rocks unaffected by phases II and III (Loma Candela Formation). Thus, although the data demonstrate that a great amount of tectonic shortening occurred in the late Paleocene/early Eocene, a significant time lag occurred before this was expressed in the topography. Extension occurred after the lithosphere isostatically adjusted to the collision. Obviously, this hypothesis does not describe some areas where arc/continent collision is actively occurring (e.g., New Guinea). A thick continental lithosphere did not enter the Cuban collision zone which may have led to a significantly slower development of topography. Thus the extension is observed at a later stage in Cuba than in other orogenic belts. In fact, it appears that the post-Miocene emergence of the Cuban archipelago [*Iturralde-Vinent*, 1969] was caused by the extension, not by the thrusting. The extension could thus be related to an overthickened crust that did not have a topographic expression. Extension of this nature could be driven primarily by crustal or lithospheric processes, not a high topography.

Phase V: Post-Early Miocene Compression

At several sites such as the Sierra de Anafe, strike-slip faults associated with a NW-SE compression overprint the normal faults. Both the normal faults and the strike-slip faults occur in the early Miocene Husillo Formation. Thus the strike-slip faults are post-early Miocene and postnormal faulting in age.

Inversion of the late formed populations of strike-slip faults results in an ESE-WNW compression at three sites and a NW-SE compression at one site (Figure 19). The σ_1 and σ_3 axes are mostly horizontal and the σ_2 axes are vertical as expected for strike-slip dominated data sets (Table 7). The Φ values are clustered around 0.50 (Table 7). The values for ANG are all low, and the values for RUP are low to acceptable.

This tectonic phase is the most enigmatic of all. Although it was only found at a few sites, the overprinting of phase IV in the Sierra de Anafe dates the phase well, and its role in the regional tectonics should be addressed. This stress direction is 90° from the direction expected from sinistral faulting along the Cayman Trough which has been active since the Eocene [*Rosencrantz et al.*, 1988]. It is also 90° different from the active σ_1 direction observed in the southern United States (Figure 20) [*Zoback and Zoback*, 1991]. Thus we attribute this last phase to local deformation within Cuba rather than to major plate motions.

Discussion

Many workers [e.g., *Pindell and Barrett*, 1990; *Mann et al.*, 1995] suggest that the Caribbean region represents a complex crustal amalgamation of continental, oceanic and oceanic plateau lithosphere that was inserted behind a generally east facing Caribbean arc system (Figure 1b). We propose that the Cenozoic evolution of the northern Caribbean margin has been dominated by escape tectonics. We use the diachronous collision between the Pannonian and Eurasian continental plates [*Royden*, 1988] as a much better documented model of escape tectonics than the northern Caribbean.

Campanian-Maestrichtian. Initial contact between a Pacific-derived, eastward moving Caribbean plate and North and South America is best documented during Maestrichtian time at the southern margin of the Yucatan Peninsula in Guatemala, Central America, where synorogenic sedimentation and northward verging folding, thrusting, and obduction of ophiolites occurred in the late Campanian-Maestrichtian [*Rosenfeld*, 1991] (Figure 20a). This deformation marks the conversion of the northern Central American Cretaceous pas-

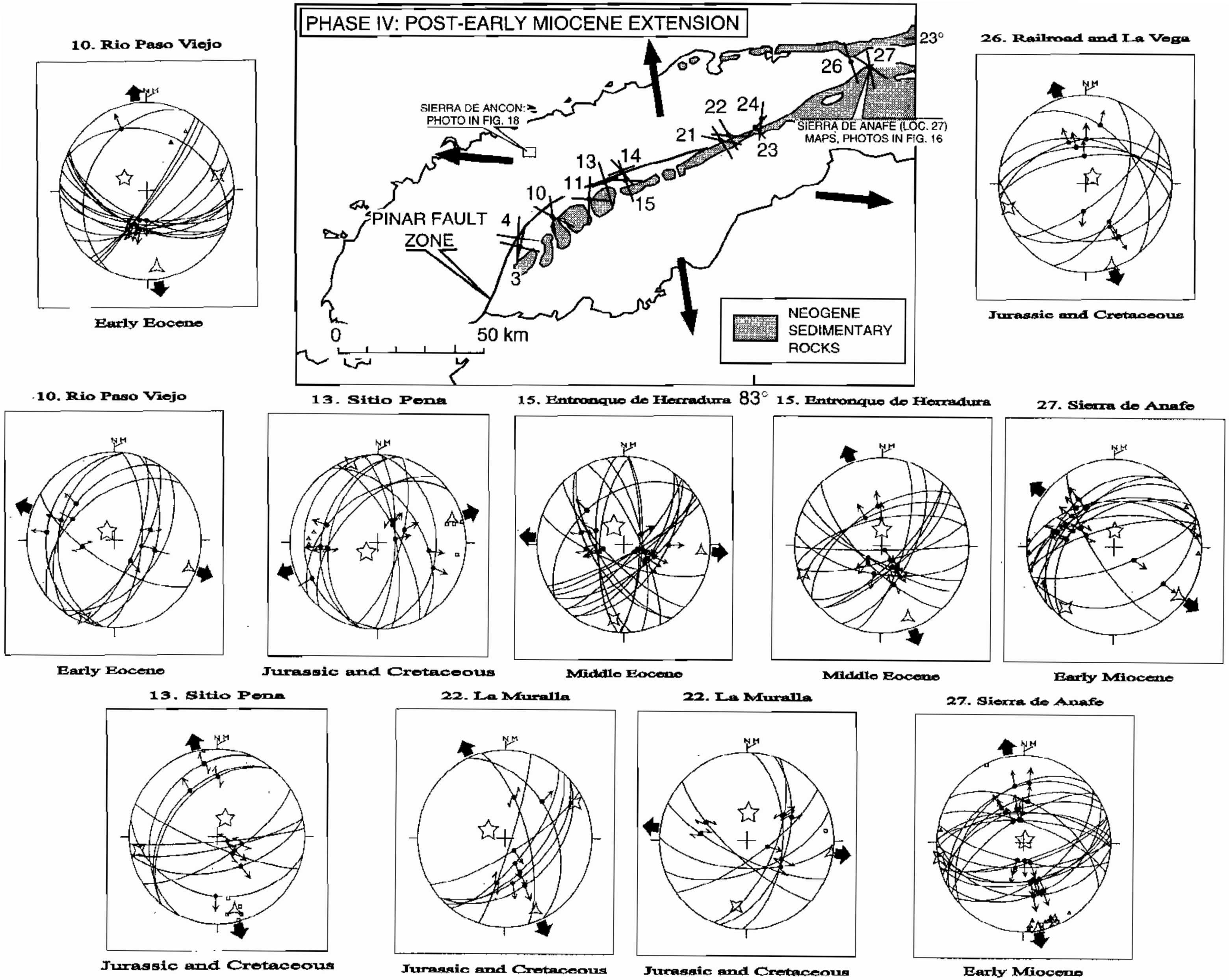

Figure 15. Tension directions (tectonic phase IV) affecting Jurassic to lower Miocene rocks are shown on the map (arrows indicate direction of tension as derived from the fault plots shown). The tension directions can be divided into generally N-S tension and generally ESE-WNW tension. Lower Miocene rocks of Sierra de Anafe (site 27) are as affected by normal faulting as any of the older sites. The only other faults that occur in the lower Miocene rocks are related to the phase V compression. Thus both phases IV and V occurred after deposition of the lower Miocene rocks.

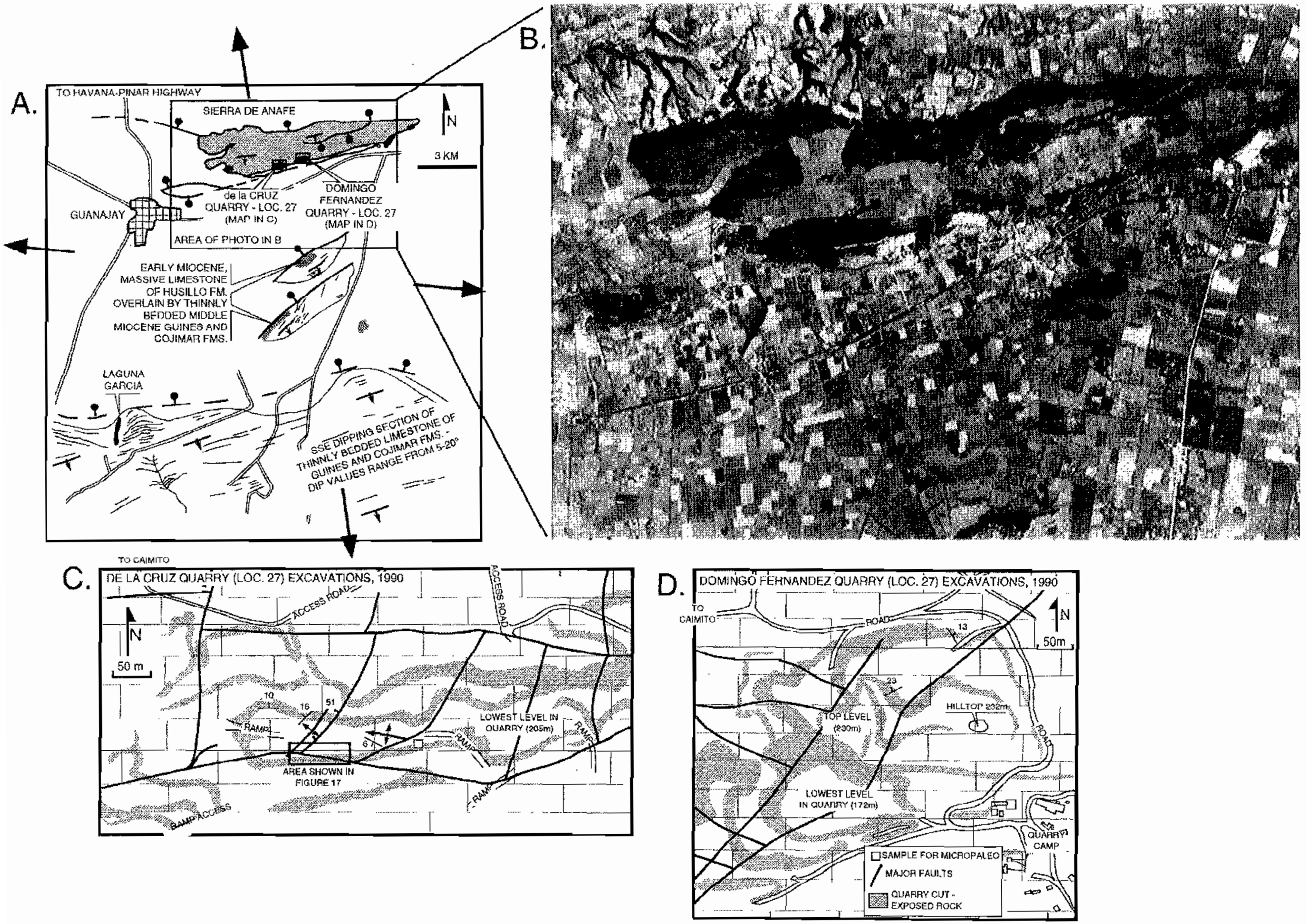
A.
TO HAVANA-PINAR HIGHWAY
SIERRA DE ANAFE
N
3 KM
GUANAJAY
de la CRUZ
QUARRY - LOC. 27
(MAP IN C)
DOMINGO
FERNANDEZ
QUARRY - LOC. 27
(MAP IN D)
AREA OF PHOTO IN B
EARLY MIOCENE,
MASSIVE LIMESTONE
OF HUSILLO FM.
OVERLAIN BY THINNLY
BEDDED MIDDLE
MIOCENE GUINES AND
COJIMAR FMS.
LAGUNA
GARCIA
SSE DIPPING SECTION OF
THINNLY BEDDED LIMESTONE OF
GUINES AND COJIMAR FMS. -
DIP VALUES RANGE FROM 5-20°
B.
TO CAIMITO
C.
DE LA CRUZ QUARRY (LOC. 27) EXCAVATIONS, 1990
ACCESS ROAD
ACCESS ROAD
N
50 m
10
16
51
6
RAMP
RAMP
RAMP
RAMP
LOWEST LEVEL IN
QUARRY (205m)
AREA SHOWN IN
FIGURE 17
RAMP ACCESS
D.
DOMINGO FERNANDEZ QUARRY (LOC. 27) EXCAVATIONS, 1990
TO
CAIMITO
ROAD
N
50m
13
23
TOP LEVEL
(230m)
HILLTOP 232m
ROAD
LOWEST LEVEL
IN QUARRY (172m)
QUARRY
CAMP
SAMPLE FOR MICROPALEO
MAJOR FAULTS
QUARRY CUT -
EXPOSED ROCK

Table 6. Phase IV (ESE-WNW Tension) Results of Fault Slip Inversion

Site	Site Name	σ_1	σ_2	σ_3	Number of Faults	Φ Value	ANG, deg	RUP, %
2	Lagunilla							
	Junta Macurijes							
	combined	269 68	022 09	115 20	04	0.36	11	36
5	Mestanzas North	053 67	163 08	256 21	04	0.25	07	23
	Mestanzas South	156 57	016 26	277 18	04	0.58	03	35
	combined	121 73	022 03	291 17	08	0.57	11	32
10	Río Paso Viejo	321 79	201 06	110 09	09	0.26	08	22
13	Sitio Peña	229 76	341 05	072 13	11	0.30	10	27
14	Rigo Fuentes	321 63	169 25	073 11	04	0.42	10	32
15	Entronque de Herradura	331 71	188 16	095 11	19	0.13	10	34
21	La Reforma	014 68	184 21	275 03	12	0.21	09	30
22	La Muralla	003 64	189 26	098 02	08	0.26	11	26
27	de la Cruz	003 75	219 13	127 09	08	0.47	09	29
	Domingo Fernandez	224 69	038 21	129 02	05	0.09	03	14
	combined	351 86	213 03	124 03	13	0.51	13	31

sive margin to a fold-thrust belt and strike-slip zone. An oceanic "free face" east of the southern promontory of northern Middle America allows the arc system to continue migrating to the northeast toward passive margin rocks of the Bahamas Platform. Northeastward migration of the northeast facing arc is accompanied by the formation of the Yucatan basin back-arc basin [*Rosencrantz*, 1990].

Latest Paleocene. Northeastward progression of the leading edge of the arc system is documented by latest Paleocene collision of the arc against the Bahamas Platform in western Cuba (Figure 20b). This event corresponds to tectonic phase I in western Cuba that is characterized by a northwestern direction of maximum compression (see inset) and by a southeast to northwest direction of overthrusting. This compression direction is orthogonal to the northeastward direction of Caribbean plate motion proposed in the Caribbean reconstructions of *Pindell and Barrett* [1990] and by *Rosencrantz* [1990] for strike-slip fault trends and the distribution of back-arc basin oceanic crust in the Yucatan basin. This northwestward direction of thrusting toward a deep-water area of thinned continental and oceanic crust in the southeastern Gulf of Mexico [*Marton and Buffler*, 1994] may have resulted from a combination of forces produced by Caribbean plate convergence in a northeastward direction and forces generated by gravity within the thickening thrust belt that acted in a northwestward direction (see *Platt et al.* [1989] for description of a similar kinematic process during continent-continent collision in the western Alps). Alternatively, phase II may have been partially concurrent with phase I, although sinistral faulting along the Pinar fault would have continued after the cessation of thrusting. In this scenario, the northwestward direction of thrusting can be viewed as a result of displacement partitioning where the plate motion is in a north-northeastward direction (see *Cashman et al.* [1992] for a description of a similar kinematic process actively occurring in northern New Zealand).

Latest early Eocene. Strike-slip deformation during the latest early Eocene included an initial phase of northeast compression (phase II) followed by a later phase of east-northeast compression (phase III) (Figure 20c). These phases affected rocks of early Eocene but not rocks of middle Eocene age that lie unconformably above them. The middle Eocene marks the beginning of a 30 m.y. period of quiescence that lasted until the early Miocene. We interpret the clockwise rotation of compression directions as reflecting the changing direction of arc migration as it attempts to move more to the east in the direction of tectonic escape as a consequence of the inability of the Cuban arc to subduct the continental passive margin of North America. Suturing in western Cuba induces clockwise rotation in the direction of collision as the forward progress of the arc system is stopped by the entry of thicker crust of the Bahamas Platform into the subduction zone. This twisting motion may facilitate the formation of a strike-slip fault in the overriding plate (Yucatan basin and Cuban island arc [*Rosencrantz*, 1990]) that is more favorably oriented for the

Figure 16. (a) Regional map of Sierra de Anafe area based on interpretation of aerial photographs and stratigraphy by *de Albear-Fránquiz and Iturralde-Vinent* [1985]. Faulted exposures of the lower Miocene Husillo Formation and middle Miocene Guines and Cojimar Formations (undifferentiated) are interpreted as horst blocks uplifted during post-early Miocene normal faulting of phase IV. The general trend of the ranges and large-scale faults is orthogonal to the north-south tension direction inferred from the fault slip analysis (Figure 15). Large solid arrows represent tension directions inferred from mesoscopic fault data collected at de la Cruz and Domingo Fernandez quarries on the Sierra de Anafe. (b) Aerial photograph taken in 1954 of the area shown in Figure 16a. Geologic maps of the Sierra de Anafe made by quarry geologists and supplemented by this study. The quarry geologists have also mapped the entire Sierra (not shown here) and found more and larger normal faults. (c) Geologic map of the quarry de la Cruz showing two trends of normal faults. These faults have larger offsets (e.g., >10 m) than most of the faults used for fault slip analysis. Nonetheless, they are entirely consistent with tension directions inferred from the fault slip analysis in this quarry (see a for location). Anticlines are interpreted as rollover folds developed along listric normal fault planes (Figure 17). (d) Geologic map of the Domingo Fernandez Quarry. The mapped faults are also consistent with the N-S and ESE-WNW tension observed at the two quarries. Note that the E-W faults are more continuous. This trend has been found throughout the Sierra de Anafe, suggesting that the N-S extension is the greater of the two.

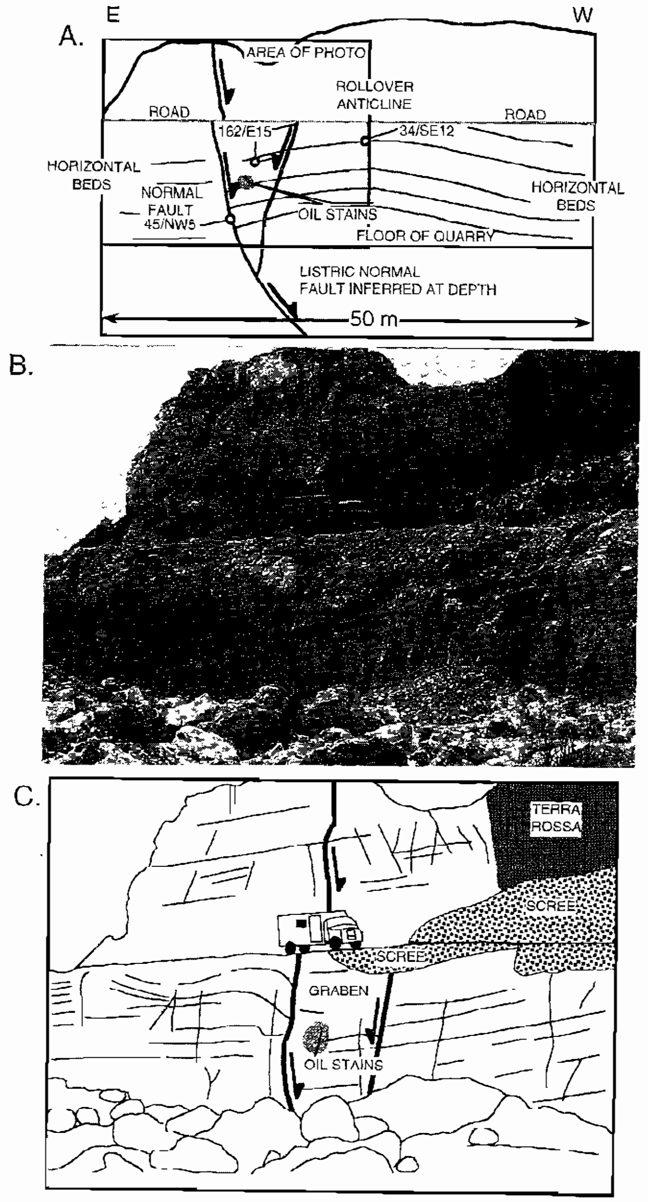

Figure 17. (a) Outcrop sketch of probable listric normal fault and associated rollover anticline deforming Husillo Formation at de la Cruz quarry. (b) More detailed photograph of fault in Figure 17a. (c) Sketch of photograph in Figure 17b.

new, more northeastward direction of relative plate motion. The formation of this fault forms a small microplate in the northern Yucatan basin that will eventually transfer from the overriding (Caribbean) plate to the underriding (North America plate).

Middle Eocene/early Miocene. The mainly shallow to deep water carbonate rocks of this age range in western Cuba are affected only by post-early Miocene tension (phase IV) and compression (phase V). These rocks were deposited in a tectonically quiescent period characterized by the gradual subsidence of the fold-thrust belt of western Cuba in a now intraplate setting. Active plate boundary collision migrates eastward to central Cuba [*Hatten et al.*, 1988, also unpublished report, 1958; *Hempton and Barros*, 1993] (Figure 20d).

Post-early Miocene extension. By Miocene time, transpressional deformation and uplift produce the present-day topographic ranges and basins in Hispaniola as arc rocks in Hispaniola encounter the southeastward continuation of the Bahamas Platform [*Mann et al.*, 1995] (Figure 20e). Western Cuba is affected by an extensional event (phase IV) with the directions of maximum tension roughly orthogonal and parallel to the trend of the Guaniguanico and Martin Mesa windows. As western Cuba is in an intraplate setting by this time, there is no obvious link between phase IV and collisional processes now occurring more to the southeast in Hispaniola and Puerto Rico.

Post-early Miocene compression. By Pliocene time, the Enriquillo-Plantain Garden fault zone is active and begins to detach the Gonave microplate from the rest of the Caribbean plate (Figure 20f). The Gonave microplate is essentially "left behind" and accreted to North America as its eastward progress is impeded by the Bahamas Platform [*Mullins et al.*, 1992; *Mann et al.*, 1995]. In western Cuba, a 120 compression postdated the post-early Miocene tension of phase IV, but we cannot establish the upper bound of the age of deformation because lower Miocene rocks were the youngest rocks

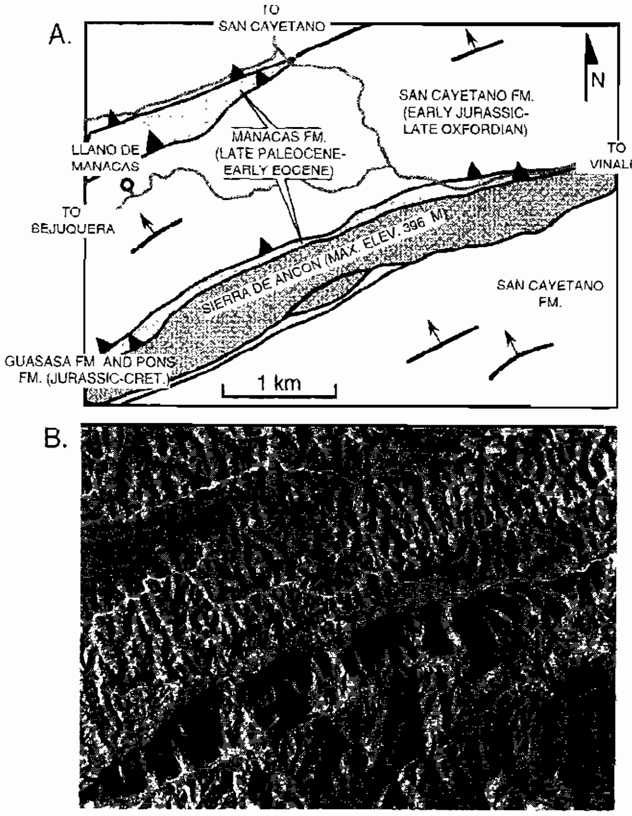

Figure 18. (a) Interpretation of aerial photograph shown in Figure 18b. The presence of Manacas Formation between the ranges composed of Mesozoic sedimentary rocks has been interpreted as strong indication for a major late Paleocene/early Eocene thrusting event [*Pszczólkowski et al.*, 1987; C.W. Hatten, unpublished report, 1957]. This general model is entirely supported earlier in this paper and by *Bralower and Iturralde-Vinent* [1997]. However, the Paleogene thrusting does not appear to account for topography observed in this photograph. The range front appears very abrupt and linear unlike that of a typical thrust belt. Thus we suggest that the ranges in western Cuba were formed during the post early Miocene tension. Location of area is shown in Figure 15. (b) Aerial photograph of the Sierra de Ancón and surrounding region.

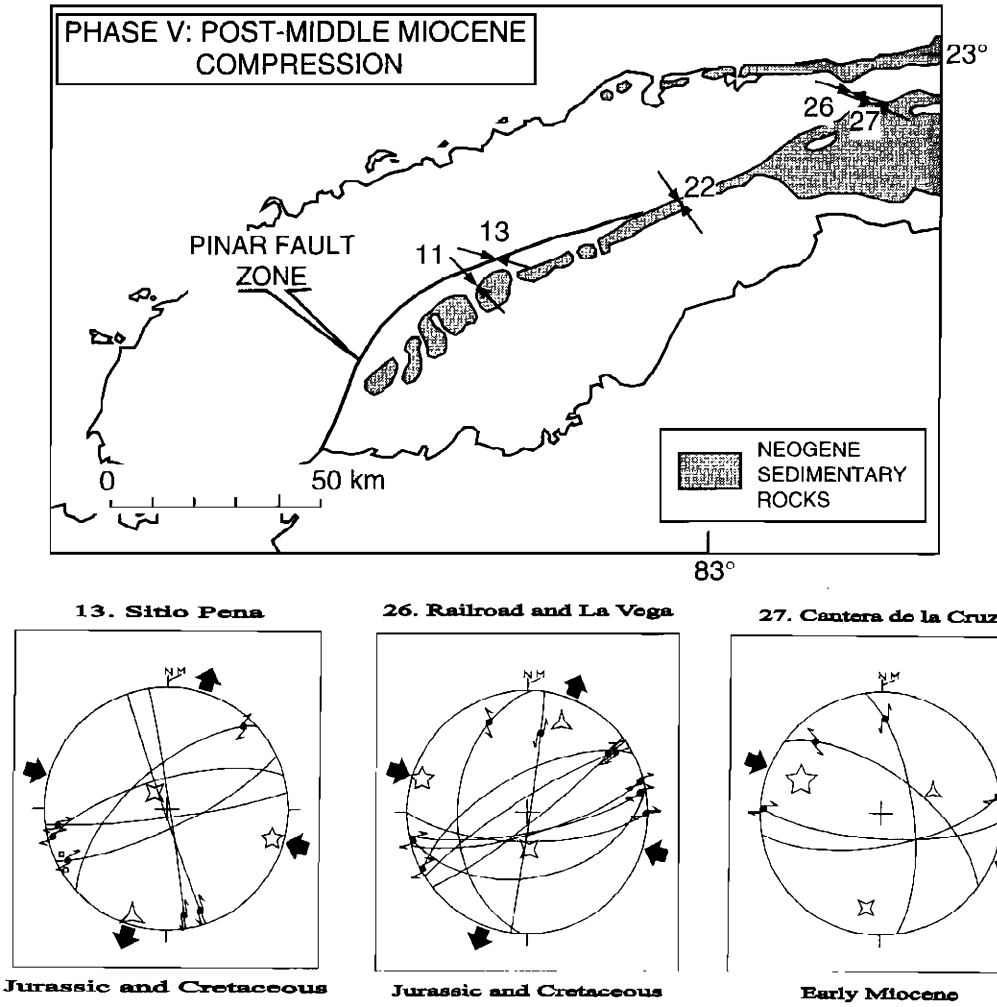

Figure 19. A final compression (tectonic phase V) is shown on the map (arrows indicate directions of compression as derived from the fault plots). The compression direction is ESE-WNW to NW-SE. Faults of this phase overprint faults of phase IV at the Sierra de Anafe (site 27) where the early Miocene limestone crops out. Phase V is the final deformation phase that we recognized in western Cuba.

from which observations were made. The 120 compression direction of this phase in western Cuba is at a high angle and therefore unrelated to the present-day 060 direction of maximum horizontal stress in the southeastern United States [*Zoback and Zoback*, 1991]. This compression event had not been previously recognized in Cuba or offshore areas, and its origin remains enigmatic.

Conclusions

By documenting the evolution of the stress directions during and after an arc/continent collision, we have reached the following conclusions: (1) The initial collision in the late Paleocene/early Eocene produced a NW-SE oriented compression, NW directed thrusting with the thrusting from SE to NW

Table 7. Phase V (NW-SE Compression) Results of Fault Slip Inversion

Site	Site Name	σ_1	σ_2	σ_3	Number of Faults	Φ Value	ANG, deg	RUP, %
13	Sitio Peña	106 11	323 77	197 08	06	0.73	07	20
22	La Muralla	320 16	073 55	220 31	04	0.46	10	37
26	Railroad tracks							
	La Vega	289 09	179 66	022 22	07	0.48	05	30
	combined	287 09	177 65	021 23	09	0.50	05	29
27	de la Cruz	292 29	188 23	066 51	04	0.29	07	36
	Domingo Fernandez							
	combined							

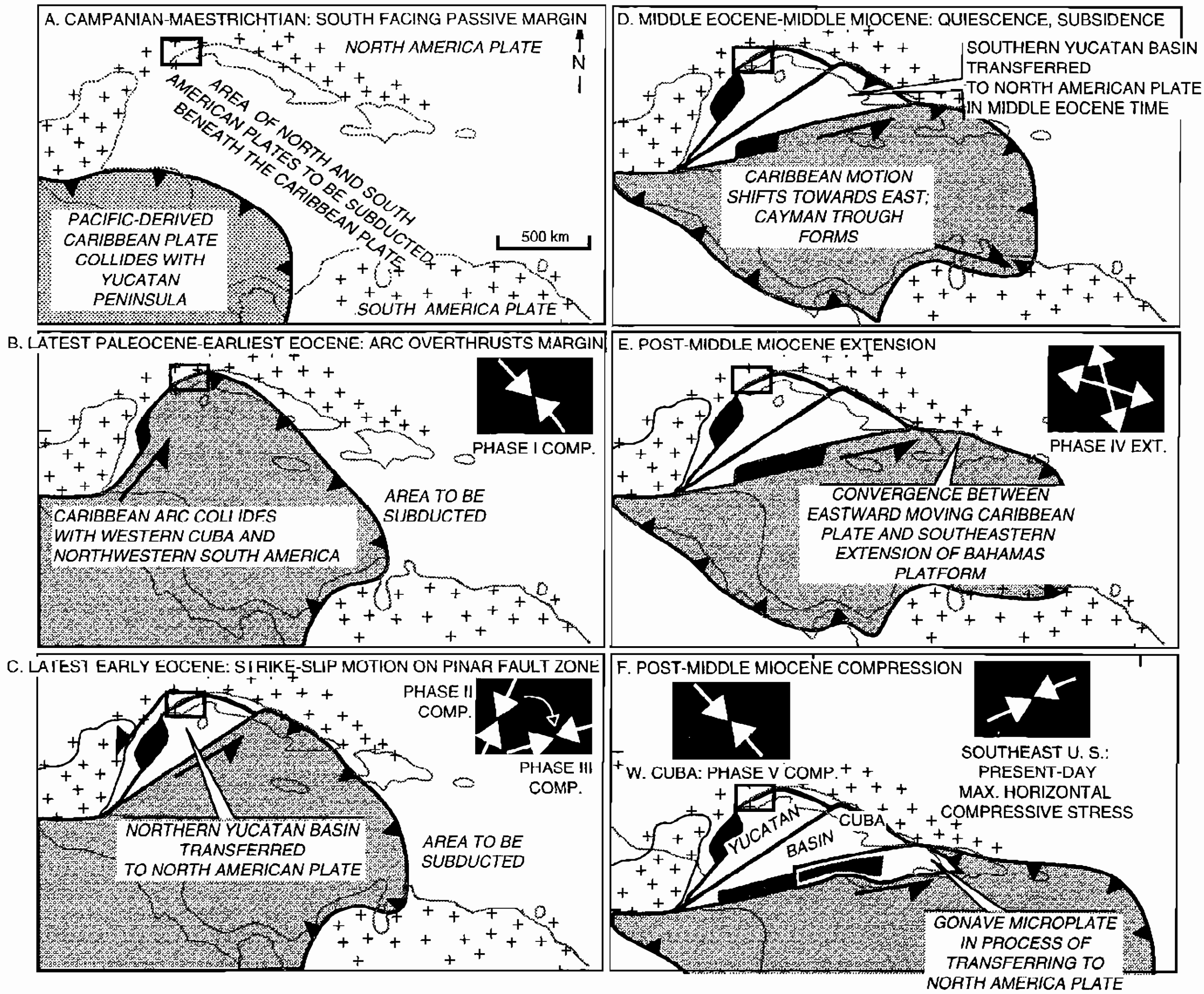

Figure 20. Tectonic setting of the Caribbean plate from Maestrichtian to Recent time (modified from *Pindell and Barrett* [1990] and *Mann et al.* [1995]). Arrows in solid boxes represent directions of maximum compressive and tensional stresses derived from this study. (a) Maestrichtian, initial collision of a Pacific-derived, eastward-moving Caribbean plate and North and South America in Central America and western South America. Western Cuba is the site of the passive margin of North America (platform and slope deposits of the Bahamas Platform). (b) Latest Paleocene/earliest Eocene, continued movement of the arc and trailing Caribbean plate leads to its collision with passive margins in western Cuba and northwestern South America. A NW direction of maximum compression is inferred during the thrusting in western Cuba. (c) Latest early Eocene, migration of collision from western to central Cuba induces clockwise rotation in the direction of collision as the forward progress of the arc is stopped by the entry of thicker crust of the Bahamas Platform into the subduction zone. Left-lateral shear occurs along the Pinar fault zone with compression directions of both phases rotating clockwise and into parallelism with the changing plate direction. (d) Middle Eocene/early Miocene, collision can advance no farther to the north-northeast above the Bahamas Platform and the present-day Cayman Trough forms as the Caribbean plate is rotated clockwise and is twisted toward a more easterly direction. The western Cuba margin is tectonically quiescent. (e) Post-early Miocene, oblique Miocene collision between the Caribbean plate and the southeastern Bahamas Platform produces tectonic transpression and uplift in Hispaniola. In northern South America, oblique collision continues to migrate along the passive margin. Post-early Miocene tension occurs in western Cuba because of postcollision adjustment to the thickened crust. (f) Post-early Miocene, by Pliocene time transpression in Hispaniola has detached the Gonave microplate. Less transpression is observed in northern South America because the direction of plate motion is roughly parallel to the passive margin. In western Cuba, a NW-SE compression occurs. Its direction does not correspond with the present-day maximum horizontal compressive stress field of the southeastern United States [*Zoback and Zoback*, 1991] and may relate to a local effect in Cuba.

(phase I). (2) The thrusting was immediately followed in the early Eocene by NNE-SSW compression related to sinistral shear on the Pinar fault zone (phase II). (3) The sinistral faulting was followed by ENE-WSW compression (phase III). The phase III faults overprint the phase II faults and only affect rocks of early Eocene and older age. The presence of an oceanic free face to the east causes the clockwise rotation of stress directions from phase I to phase III. (4) After a 30 m.y. period of

tectonic quiescence, two contemporaneous tension directions (170 and 120) affected lower Miocene rocks. (5) A 120 compression overprinted the normal faults associated with the tension.

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