An Overview to the Tectonics of Cuba

5

Jorge Luis Cobiella Reguera

Abstract

Two main structural levels or stages can be distinguished in the geological architecture of Cuba. The lower stage is the socle, a great rock complex, mainly formed by Jurassic–Eocene rocks, unconformably resting below the cover. The socle is divided into three major complexes, according to their litho-structural features and rock age: (a) the Proterozoic–Paleozoic basement, (b) the Mesozoic basement, and (c) the Paleogene folded and thrust belt. A small part of the socle is represented by Precambrian (Grenvillian) rocks, only known by tiny outcrops in the northcentral Cuban mainland, whereas the Paleozoic eratem is only known in the sea floor of the Cuban Exclusive Economic Zone of the SE Gulf of Mexico. The Mesozoic basement consists of four rock complexes of very different nature (a) The Mesozoic passive paleomargin of the SE North American plate (NAP). Whereas the NAP contains autochthonous or parauthoctonous massifs, the remaining Mesozoic units are tectono-stratigraphic terranes, separated by tectonic contacts between them and with the NAP. These terranes are (b) the northern ophiolite belt (NOB), (c) the Cretaceous volcanic arcs (KVA), (d) the southern metamorphic terranes (SMT). The Mesozoic basement attains a wide distribution both in outcrops and subsurface. The Paleogene folded and thrust belt contains four regional structures: the foreland basin, the piggyback basins, the Sierra Maestra–Cayman Ridge volcanic arc, and the Middle and the Late Eocene Eastern Intramontane Basin. However, complicated, their mutual relationships are quite much clearer than that prevailing in the Mesozoic basement. The Eocene–Quaternary cover contains little disturbed beds, without magmatic or metamorphic rocks. The nearness of SE Cuba to the Caribbean/North American plate boundary prints its cover with some special features.

Keywords

Tectonics • Gulf of Mexico • Caribbean • North American Paleomargin • Cuba • Ophiolite

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Abbreviations

NAP	North America Paleomargin
NOB	Northern Ophiolitic Belt
KVA	Cretaceous Volcanic Arcs
KVAT	Cretaceous Volcanic Arc Terrane
SMT	Southern Metamorphic Terranes
Fm	Formation
TSU	Tectono-Stratigraphic Unit
IGP	Instituto de Geología y Paleontología
CEEZ	Cuban Exclusive Economic Zone
APS	Alturas de Pizarras del Sur tectono-stratigraphic unit
SO	Sierra de los Órganos tectono-stratigraphic unit
SR-APN-E	Sierra del Rosario-Alturas de Pizarras del Norte tectono-stratigraphic unit
PgB	Paleogene Basin
N-Q	Neogene–Quaternary
PG	Pan de Guajaibón
R	Remedios tectono-stratigraphic unit
CC	Cayo Coco tectono-stratigraphic unit
P	Placetas tectono-stratigraphic unit
Cj	Camajuaní tectono-stratigraphic unit
DSDP	Deep Sea Drilling Project
K	Potassium
Ar	Argon
GNL	Guacanayabo–Nipe Bay lineament
MC	Mabujina Complex
HT/MP	High-Temperature/Mid-Pressure metamorphism
MTU	Main Tectonic Unit
PFB	Paleogene Foreland Basin
FZ	Fault Zone
T-Cr	Turquino–Cayman Ridge volcanic arc
COEB	Central Oriente Eocene Basin
PBB	Piggyback Basins
OFZ	Oriente Fault Zone
PFZ	Pinar Fault Zone
TFZ	La Trocha Fault Zone
SDB	Santiago Deformed Belt
OFZ	Oriente Fault Zone
SWB	Southwestern Cuban Basin
My	Millions years
U-Pb	Uranium–lead

5.1 Introduction

During the last 25–30 years the publications on the geology of Cuba have been very limited, particularly, those related to the regional tectonics research suffered a remarkable decrease during the 90s and first years of the twenty-first century. However, in the 80s of the twentieth century, several important achievements in the field of the regional geology, especially in its cartography were attained: two geological maps, embracing all the Cuban territory at scale

1:500,000 [112] and 1:250,000 [110], and the tectonic map 1:500,000 [111] stand as major achievements. Several books devoted to some results on the knowledge of the tectonics and stratigraphy of almost 50% of its territory appears between 1983 and 1987. In spite of these results in the advance of the geological knowledge, from 1970 to 1990, a significant part of this information attained limited divulgation in journals, even in Cuba.

This dramatic contrast in only a few years is tightly related to the difficulties and severe stress in the national economy after the international events developed between 1987 and 1992.

In the next pages, the author presents and discusses some general ideas on several items of the Cuban regional tectonics developed during almost 50 years.

5.2 Materials and Methods

From 2013, the current author works on a project of the Instituto de Geología y Paleontología (IGP), devoted to assemble a tectonic map to support the information for the Metallogenic Map of Cuba at scale 1:250,000 [24].

In the preparation of this chapter, we devoted a special attention to the reworking of the information obtained by field Cuban and foreign geologists in many localities of the national territory, in the search of a plate tectonics interpretation from the old data. There is much excellent information disseminated, including reports more than 80 years old, that still can be used, i.e., the fine reports of the geologists from Utrecht University (Holland) in the early decades of the twentieth century, the reports of the U.S. Geological Survey during the 40s and 50s, several isolated papers on thematic researches developed by the IGP during the last 60 years, and many others. A special place corresponds to the reports and maps related to the program for the geological cartography of the Cuban territory developed by the IGP from 1971 to 1989, especially the Geological (1988) and Tectonic (1989) maps of Cuba. The author has worked more than 50 years in different places of the country, a fact very important to assume this task but, obviously, he does not know every place and also the quality of the geological information from different territories is not homogenous, as it occurs in all countries.

In our approach, a particular attention is devoted to integrate the relationships between the Cuban territory and its surroundings, a subject that will be visited several times along the paper. Another subjects with many questions are the age of several main tectonic events, because of their poor datation and, therefore, the uncertain correlation between distinct territories. In some cases, the information on the nature and composition of the sedimentary record as well as the sedimentary structures present, fundamental for paleogeographic interpretations is scarce. Some cases are discussed.

There are many interesting items on the tectonics of Cuba but, within the limits of the current publication, only a small part of the problems could be visited. We will present an overview of the subject and try to introduce a new approach to some of them. Obviously, our experience is not uniform in all the fields, and several items will not receive the attention that each specialist demands.

5.3 Results and Discussion

Cuba and its surroundings are a geological mosaic located in the southern border of the North American plate. Rocks from many different origins, with Proterozoic to Quaternary ages, belong to this puzzle belt, extended along the southern border of the plate, from northern Central America to the Virgin Islands. From the Middle Eocene, this belt has been dissected by several great faults, related to the development of some oceanic depressions (Cayman Trough and Yucatan Basin) in the Mesoamerican area.

Two main structural levels or stages can be distinguished in the geological architecture of Cuba. The lower stage is the socle, a great rock complex, mainly formed by Jurassic–Eocene rocks, unconformably resting below the cover.

The socle is divided into three major complexes, according to their litho-structural features and rock age: (a) the Proterozoic–Paleozoic basement, (b) the Mesozoic basement, and (c) the Paleogene folded and thrust belt.

A small part of the socle is represented by Precambrian (Grenvillian) rocks, only known by tiny outcrops in the northcentral Cuban mainland, whereas the Paleozoic eratem is only known in the sea floor of the Cuban Exclusive Economic Zone of the SE Gulf of Mexico. The Mesozoic basement consists of four rock complexes of very different nature: (a) the Mesozoic passive paleomargin of the SE North American plate (NAP). Whereas the NAP contains autochthonous or parauthoctonous massifs, the remaining Mesozoic units are tectono-stratigraphic terranes, separated by tectonic contacts between them and with the NAP. These terranes are (b) the northern ophiolite belt (NOB), (c) the Cretaceous volcanic arcs (KVA), (d) the southern metamorphic terranes (SMT). The Mesozoic basement attains a wide distribution both in outcrops and subsurface.

The Paleogene folded and thrust belt contains four regional structures: the foreland basin, the piggyback basins, the Sierra Maestra–Cayman Ridge volcanic arc, and the Middle and the Late Eocene Eastern Intramontane Basin. However complicated, their mutual relationships are quite much clearer than those prevailing in the Mesozoic basement.

The Eocene–Quaternary cover contains little disturbed beds, without magmatic or metamorphic rocks.

5.3.1 The Premesozoic Basement. Precambrian and Paleozoic Rocks

A main achievement in the regional geology of the Greater Antilles, attained during the last 25 years of the twentieth century, is the discovery of Precambrian and Paleozoic rocks in Cuba and its surroundings.

Some of the main papers, dealing with the Cuban Precambrian rocks, are as follows: [81, 109, 113, 119, 121, 122]. As it is evident, however, the theoretical interest, because these rocks are the unique reference of very old events in the northern Caribbean, the problem of the Precambrian rocks in Cuba received very little attention during the last 30 years. The Precambrian basement is exposed in several small outcrops in northern central Cuba [101, 109, 122]. The Precambrian rocks are represented by phlogopitic marbles. Somin and Millán [121] obtained K–Ar radiometric ages of 910 and 945 My in Sierra Morena. Later Renne et al. [113] obtained $^{40}Ar/^{39}Ar$ ages of 903 My from phlogopite in marbles of the Socorro complex. The marbles are possibly intruded by Jurassic (172 My) granitoid plutons [113]. An arcosic regolith, containing granite and marble clasts, rests at the floor of the overlying Upper Jurassic–Lower Cretaceous sequence. Later, additional data on this subject will be displayed.

Meanwhile, there are some Precambrian outcrops in Cuba, we do not have evidences on Paleozoic rocks inland. The direct information on a Paleozoic basement comes from the DSDP wells 537 and 538A, located in the Cuban Exclusive Economic Zone (CEEZ, Fig. 5.1) of the SE Gulf of Mexico Basin, drilled in January 1981 [119]. According to these authors, in the first well, the basement rocks were phyllites with Ar/Ar ages of circa 449 and 456 My. In the hole 538A, the basement is represented by biotitic gneisses yielding radiometric ages of 496 and 501 My. These Lower Paleozoic rocks are intruded by diabase dykes of, at least, two generations of radiometric ages. The younger intrusive event (165–163 My) correlates with the mafites of El Sábalo Formation in western Cuba. The oldest one intrusions are 190 My [119].

Pszczolkowski [103] found another evidence on the existence of Paleozoic rocks very near to Cuba in the clasts of silicified limestones with Upper Carboniferous and Permian *fusulinids* (benthic foraminifera) from the Upper Jurassic beds of the San Cayetano Formation, near Cinco Pesos, in Sierra del Rosario Mountains. We will see that this unit is part of a Jurassic Paleo Delta, accumulated at the southwestern margin of Laurasia supercontinent (the North American plate).

According to Hutson et al. [51], who studied the radiometric age of 67 muscovite detrital grains in four samples from the Jurassic San Cayetano Formation, the abundance of grains with Paleozoic ages (79%) suggests a provenance from a Taconic orogenic source, probably located in

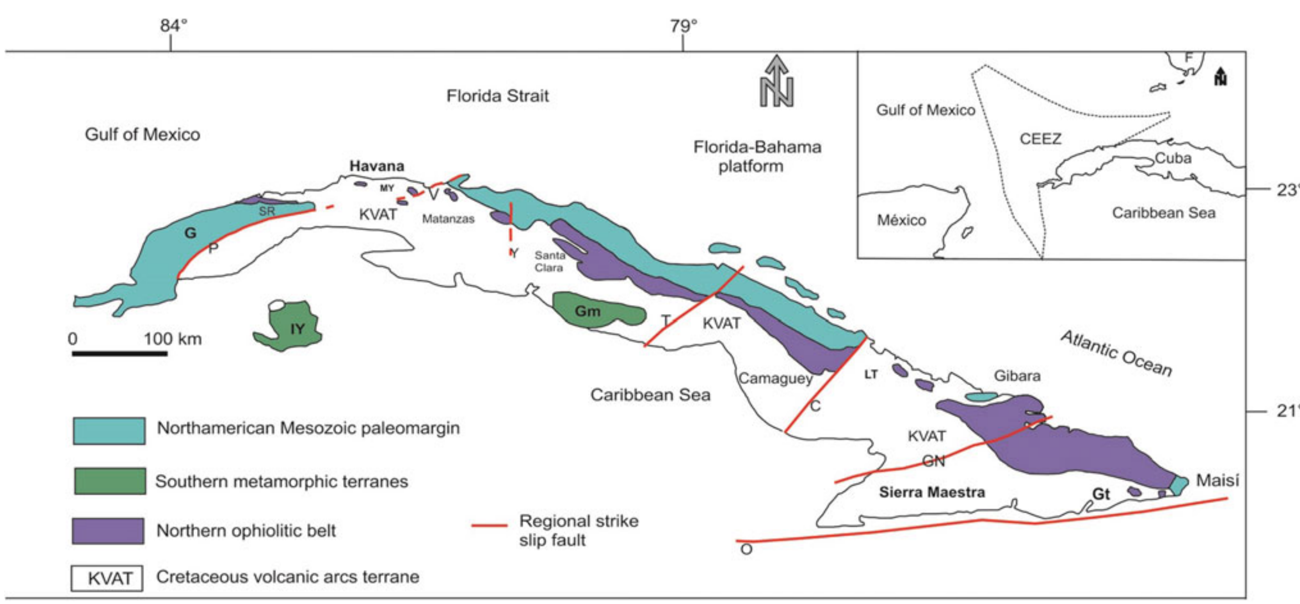

Fig. 5.1 Major strike-slip faults of Cuba (red lines) and Precenozoic regional structures G: Guaniguanico Mountains, SR: Sierra del Rosario Mountains, Gm: Guamuhaya Massif, IY: Isla de la Juventud, V: Varadero lineament, P: Pinar fault zone, Y: Yabre lineament, T: La Trocha lineament, C: Camagüey lineament, O: Oriente fault zone, CEEZ: Cuban Exclusive Economic Zone in the Gulf of Mexico, MY: Mayabeque Province, LT: Las Tunas Province, GT: Guantánamo, F: Florida Peninsula

Yucatan, because rocks of such ages are unknown in Florida and northernmost South America, the other probable sources, according to different precedent paleotectonic models.

Finally, Rojas-Agramonte et al. [116] studied the radiometric ages from the zircon grains in two sandstone samples of the same lithostratigraphic unit in Alturas de Pizarras del Norte. These authors also consider that part of the zircon grains could be derived from Paleozoic source rocks in Yucatán.

5.3.2 The Mesozoic Basement

Structurally, the units of the Mesozoic basement extend parallel to the axis of the main island of the Cuban Archipelago (Fig. 5.1). It represents the most complicated socle element. The northernmost unit is the North American passive continental paleomargin (NAP) now outcropping as part of a fold-thrust belt, along the northern edge of the Cuban mainland. The northern ophiolite belt (NOB) and the Cretaceous volcanic arcs terrane (KVAT) lie with tectonic contacts upon the paleomargin rocks, whereas farther southward outcrop the southern metamorphic terranes.

5.3.2.1 The Passive Mesozoic Continental Margin of North America (NAP)

The NAP includes a variegated group of deposits and some mafic tholeitic igneous rocks, accumulated upon an extensional continental margin, from the Jurassic to the Late Cretaceous (locally Paleocene). Three areas with a particular development of the NAP stratigraphy can be distinguished: the mountains of Guaniguanico Cordillera, in westernmost Cuba; northcentral Cuba, from La Habana to NW Holguin Province and Maisí, in the eastern tip of the island (Fig. 5.1).

The Guaniguanico Cordillera. In the low mountains of westernmost Cuba, a great nappe pile, several kilometers thick, outcrops. Its tectonic style was discovered during the field researches at Sierra de los Órganos in the twentieth century (50s) [46, 114]. Along the southern fringe of Guaniguanico Cordillera the thrust sheets are cut by the Pinar fault zone, separating the Jurassic–Cretaceous rocks from the Eocene–Quaternary cover (Los Palacios Basin, Fig. 5.2). Five tectono-stratigraphic units (TSU), each with its own stratigraphy and structural style, are represented in the Cordillera (Figs. 5.2)There are three lower units: Sierra de los Órganos (SO), Alturas de Pizarras del Sur (APS), and Sierra del Rosario-Alturas de Pizarras del Norte-Esperanza (SR-APN-E). Here essentially the structure of the socle is a great antiform made by nappes, with its western two-thirds forming a NW convex arc [17, 19, 30, 61, 92, 97, 99, 107, 104, 108]. In the eastern third (Sierra del Rosario mountains), the SR-APN-E TSU presents a general picture of thin north dipping tectonic sheets, except locally, where south-dipping structures outcrop [29].

The oldest Mesozoic deposits belong to the San Cayetano Formation [39], a thick siliciclastic complex, accumulated in a large Jurassic delta. Oxfordian diabase sills and basaltic

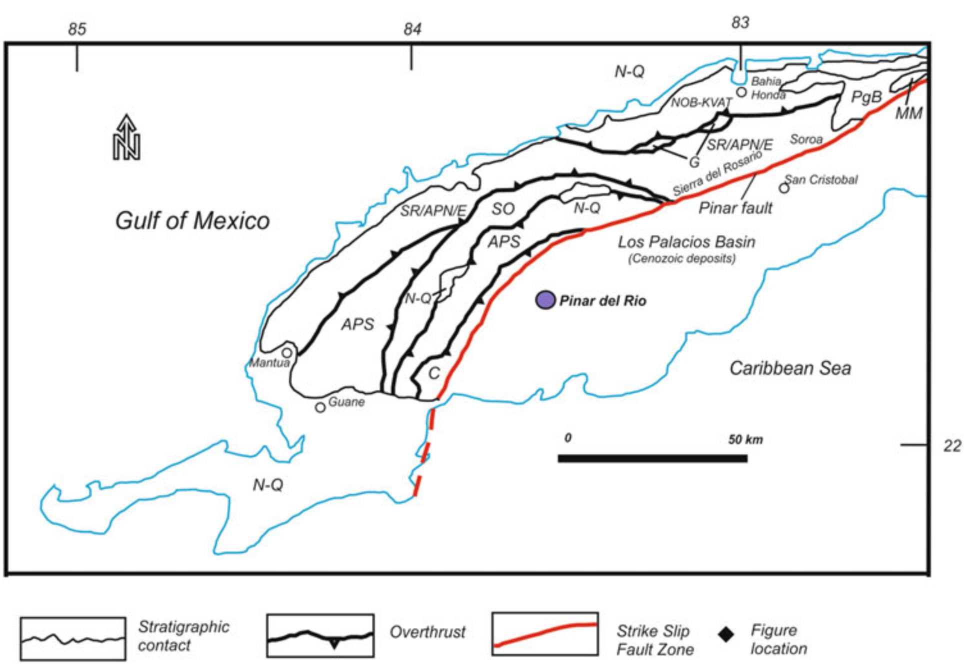

Fig. 5.2 The regional structures below the cover in western Cuba. Modified from Cobiella Reguera [19]. SO: Sierra de los Órganos TSU,APS: Alturas de Pizarras del Sur TSU; SR-APN-E: Sierra del Rosario-Alturas de Pizarras del Norte-Esperanza TSU; G: Pan de Guajaibón TSU; C: Cangre Belt TSU; NOB-KVAT: Northern Ophiolite Belt and Cretaceous volcanic arc terranes; PgB: Paleogene Basin (Cover); MM: Martin Mesa uplift (outlier of SR-APN-E); Cover: N-Q: Neogene–Quaternary deposits

pillow lavas (Fig. 5.4, El Sábalo Formation) appear frequently near their transitional contact with the Oxfordian carbonate beds of the overlying sequence [14, 14, 107, 108]. Evidences about the basement lying below the San Cayetano Formation still remain unknown and, probably, a huge decollement surface marks this lower contact. Haczewski [45], in a detailed sedimentological research, distinguishes nine facies in San Cayetano Basin and considers that their deposition occurs in the frame of a widespread deltaic environment (see also [4]), where the SO and APS contain alluvial and litoral marine deposits and SR-APN-E beds contain the deeper marine turbidites. More recent studies, supported on (a) the decrease in the quartz grain percent and the increase in feldspar + rock grain content in the San Cayetano sandstones, (b) the areal distribution of the Haczewski's facies model in the Cordillera nappe pile, and (c) the systematic structural evidence in their beds of a northward vergence [17, 28, 100], conclude that the lower units (SO and APS) represent the original northern part of the Jurassic delta and SR-APN-E belong to the primary southern locations. Therefore, the sediment source was located toward the N-NW of the delta.

Above the siliciclastic beds rests an Oxfordian–Cenomanian sequence (Fig. 5.3), whose lower beds conform a transitional terrigenous-carbonate middle–upper Oxfordian packet. In Sierra de los Órganos TSU, they belong to a 160-m-thick carbonate ramp, the Jagua Formation, whereas in Sierra del Rosario-Alturas de Pizarras del Norte-Esperanza unit, the same interval corresponds to deeper water deposits (Francisco Formation), represented by argillites and well-bedded micritic limestones, only a few meters thick, accumulated at neritic depth under restricted environments [30, 108]. An unconformity appears at the Oxfordian/Kimmeridgian contact. In Sierra de los Órganos TSU, a 650-m-thick Kimmeridgian-lower Tithonian carbonate bank (the Guasasa Formation) began a great sedimentary sequence [98, 77]. The overlying lower Tithonian–Cenomanian strata are deep water limestones with some cherty interbeds showing a clear trend to deeper water sediments with time. In SR-APN-E (Fig. 5.5), a similar phenomenon appears, but terrigenous and carbonate turbiditic beds are frequent up to the Aptian or Albian. In this TSU, thin and very scarce tuff beds appear from the Aptian [17]. This suggests a possible geographic connection with the Greater Antilles Cretaceous volcanic arc, active at that time. Thin Turonian strata are reported in some isolated localities [99, 108]. A conspicuous and well-developed Coniacian–Maastrichtian hiatus (the Upper Cretaceous Unconformity) marks the stratigraphic column of the Mesozoic paleomargin in the Guaniguanico Cordillera, the SE Gulf of Mexico and the NAP in northcentral Cuba [20]. Only in a few locations in the eastern SR-APN-E unit, Campanian beds have been recorded (Moreno Formation, [42, 104, 108]). In this lithostratigraphic unit, together with carbonate sediments, there are some tuffs and volcanoclastic beds, again suggesting the proximity of a volcanic source.

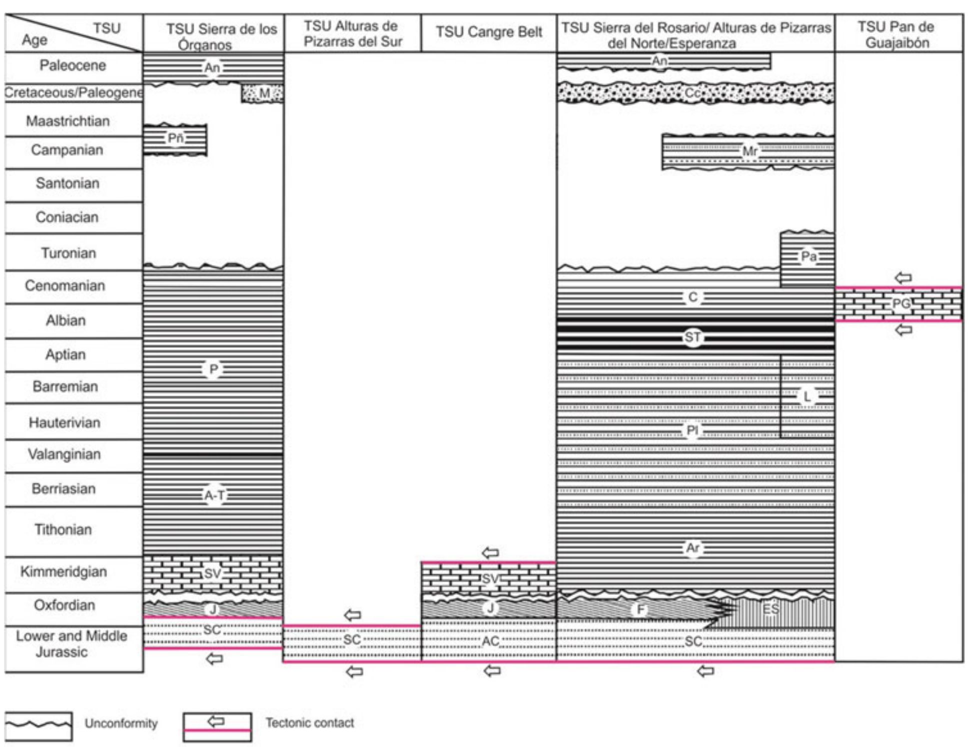

Fig. 5.3 Lithostratigraphic columns of the Guaniguanico Cordillera TSU. An: Ancon Fm.; M: Moncada Fm.; Peña Fm.; Pons Fm.; A-T (El Americano, Tumbadero and Tumbitas members of Guasasa Fm.); SV: San Vicente Fm.; J: Jagua Fm.; SC: San Cayetano Fm.; Arroyo Cangre Fm.; Mr: Morena Fm.; Pa: Pinalilla Fm.; C: Carmita Fm.; ST: Santa Teresa Fm.; L: Lucas Fm.; Pl: Polier Fm.; Ar: Artemisa Fm.; ES: El Sábalo Fm. Modified from Cobiella Reguera [19]. See also Pszczolkowski [108]

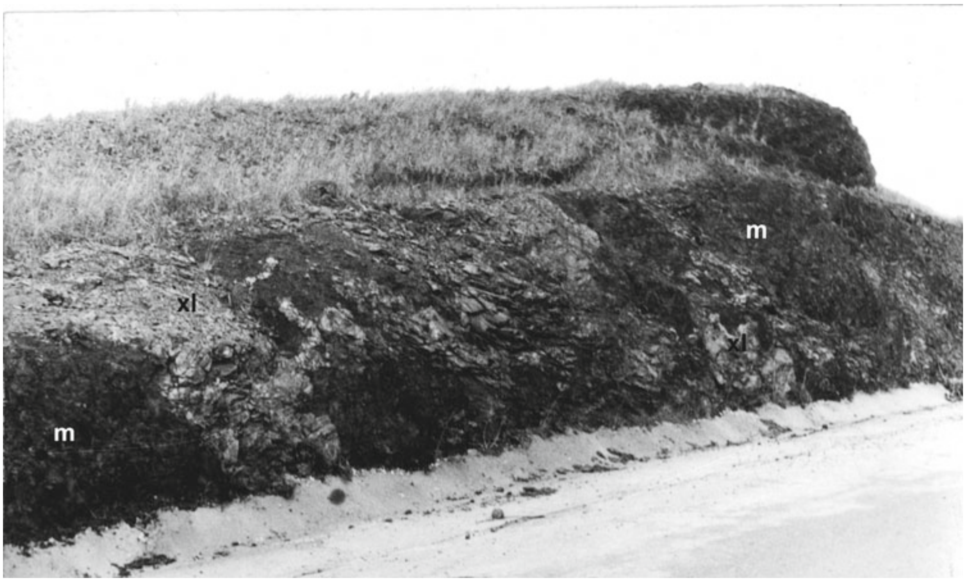

Fig. 5.4 Outcrop of El Sábalo Fm., with a mix of mafic rocks (basalt and diabase-m) and xenoliths-x, of thin-bedded Upper Jurassic limestones and shales, containing complex synsedimentary folds

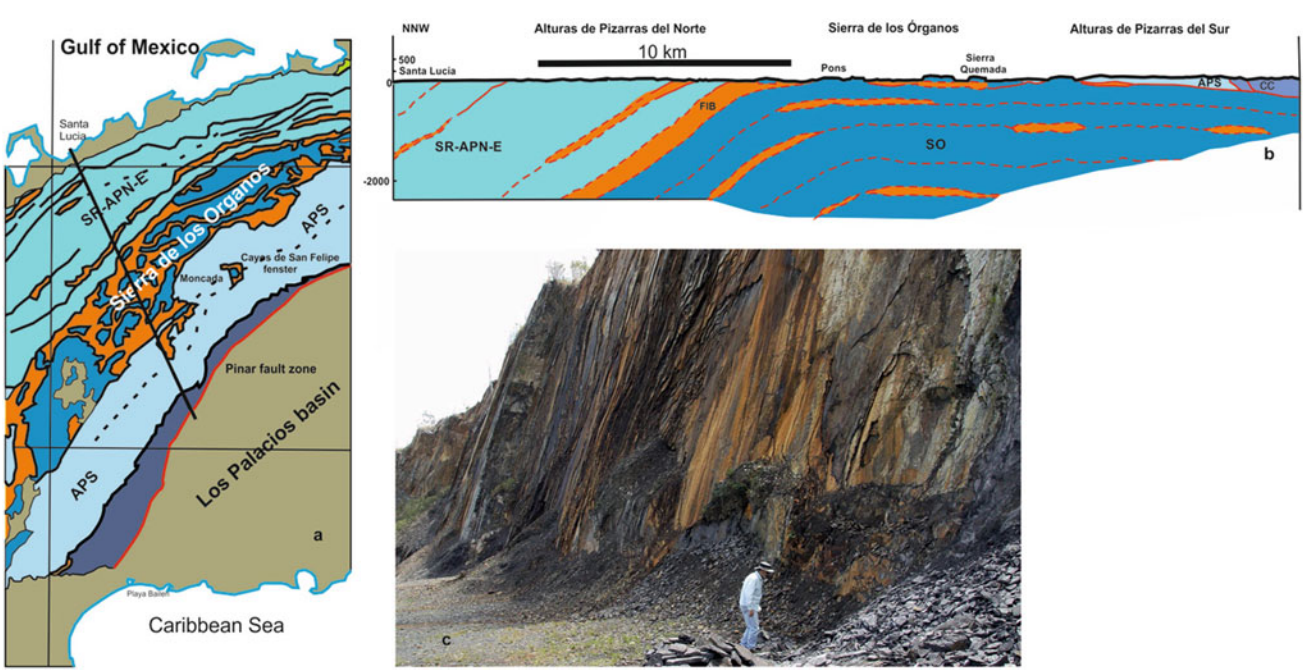

Fig. 5.5 Schematic map (**a**) and tectonic profile (**b**) along the central part of Guaniguanico Mountains, from Pinar fault zone to the northern coast, near Santa Lucia. Compare the flat lying nappes in APS and SO TSU with the north dipping linear structures in the SR-APN-E. **c** North dipping lowermost Cretaceous beds at Vegas Nuevas quarry, near La Palma, SR-APN-E

The western sector of the NAP is only with Paleocene deposits. In SR-APN-E, the lower part is a thick clastic K/Pg boundary deposit (Cacarajícara Formation, Fig. 5.3) with variable thickness (from meters to several hundred meters). The lower part of the unit has very coarse-grained deposits from debris flows, avalanches, and turbiditic currents. Meanwhile, the upper part is a fining upward massive to poor stratified calcarenites to calcilutitic beds, the homogenite of Tada et al. [126], see also Cobiella Reguera et al. [20]. In the SO unit, Cretaceous/Paleogene boundary beds are known only in one locality [5, 126] represented by tsunamic deposits, less than 2 m thick, very rich in ejecta clasts derived from the asteroid impact at Chicxulub, Yucatan, Mexico. The differences in thickness and composition in the K/Pg boundary deposits between both localities are related to the coeval regional geomorphology in the SE Gulf of Mexico–NW Caribbean area [20]. In both areas, the Paleocene to Lower Eocene beds belong to the thin and well-stratified carbonate Ancón Formation. We will return later to the extraordinary K/Pg boundary deposits from Cuba.

The nappes (tectonic sheets) represent the most remarkable structural element in the Sierra del Rosario mountains geology [104]. These structures were discovered during the geological cartography in the 70s and 80s. According to well data, the SR-APN-E thrust pile attains vertical thickness of circa 5 km in the NW Pinar del Rio Province [19]. Because there is not a thick regional rigid bed (as it occurs with the San Vicente Formation in SO, [92, 98], and thin-bedded terrigenous strata are abundant [29, 107], the SR-APN-E represents an excellent example of thin skin tectonics. The deformational features inside each nappe depend on the bed lithologies and thickness, its position with relation to the over thrust sheet floor and the depth of the deformation. In the well-bedded formations (Polier, Artemisa, Santa Teresa and others, Fig. 5.3), tight isoclinal folding frequently develops. In these successions, each strata tends to slide along its bedding planes, particularly where argillites are involved. Therefore, many faults, breccia zones, and tectonic lenses follow the stratification [29] and, frequently, hydrocarbon prints accompany them. In the eastern Sierra del Rosario, the total vertical thickness of the nappe pile is no less than 2 km. In the Alturas de Pizarras del Norte and the northern coastal lowlands, well data reveal a thin skin tectonics pattern from the Earth's surface up to no less than 5 km deep [23, 112].

The Pan de Guajaibón (PG) is the higher and northernmost tectonic unit of the Guaniguanico Mountains tectonic pile. Geographically, it belongs to Sierra del Rosario highlands; however, it is "mogote-type" geomorphology. The unit contains the homonymous lithostratigraphic unit, with circa 500 m of shallow water massive too thick bedded, northward dipping carbonate deposits of Albian–Cenomanian age [35]. The rocks are karstified, with some small bauxite deposits, probably derived from the weathering and erosion of igneous regolith [70].

An important role in the tectonic style of Guaniguanico Mountains plays the lenses of syn tectonic lower Paleogene beds and serpentinitic mélanges imbricated within the Mesozoic paleomargin deposits schematically illustrated in the tectonic map and profile of the central part of Guaniguanico Cordillera (Fig. 5.5). Whereas the serpentinitic mélanges are abundant in the SR-APN-E unit, in the APS unit they are much less frequent and the discrimination of the individual nappes is less effective. This item will be discussed additionally in the epigraph devoted to the lower Paleogene Foreland Basin and the Cuban orogeny.

Fig. 5.6 Breccia in the San Adrian diapir, Mayabeque Province. According to Meyerhoff and Hatten [78], the main lithologies in the clasts are different types of limestones (those fine grained could contain radiolarian and Nannocunus), metamorphic rocks (marbles and quartz–mica schists), quartzose sandstones, and isolated metric lenticular blocks of serpentinite. Additionally, in the formation appear some grains of pyrite, tourmaline, and apatite

The North American paleomargin in central Cuba. From Havana to NW Holguin Province, the NAP displays a remarkable zonation, discovered by the oil geologists working in Cuba during the 50s of the twentieth century that developed several fine schemes (Fig. 5.1). We will use the most recognized terms in the last decades, proposed in the zonation model by Ducloz and Vaugnat [33]. It includes, from north to south, the following four tectono-stratigraphic units: Cayo Coco (CC), Remedios (R), Camajuaní (Cj), and Placetas (P). Only the last one shows features relating it to the Upper Jurassic–Cretaceous sections in the SR-APN-E TSU of the Guaniguanico Mountains. The essential features of each TSU are discussed in several papers (see [17, 61, 67] and others). A brief review follows.

Cayo Coco and Remedios TSU represent the southern boundary of the Florida–Bahamas platform, and the first is mainly known from subsurface geology. They have very similar pre-Aptian sections, with Middle Jurassic. Evaporites (San Adrian and Punta Alegre formations, Fig. 5.6), probably coeval with the Gulf of Mexico salts [1, 61, 67]. In northern Villa Clara and Sancti Spiritus, about 1800 m of evaporites and carbonates (Cayo Coco Formation) conform the Upper Jurassic–Aptian record in the CC TSU, whereas the evaporites are absent southward, in the neritic carbonates of the R TSU. A dramatic facies change occurs in the upper Aptian–lower Turonian beds of the CC TSU, represented by hemi-pelagic carbonates. A similar deepening is recorded by the Albian–Turonian carbonate turbidites (Vilató Formation), accumulated in narrow basins (grabens) at the southern border of the Remedios TSU, in Camaguey [61]. These events probably correlate with the fracturing of the southern border of the Florida–Bahamas Jurassic–Middle Cretaceous mega platform. At the same time, more than 2000 m of shallow carbonates settled upon most of the Remedios bank (Palenque and Purio formations). Coniacian to Campanian deposits are unknown in the Remedios bank, resting the Maastrichtian carbonate beds on similar middle Cretaceous lithologies.

The southern half of the NAP in central Cuba is occupied by the Camajuaní and Placetas TSU. The first one outcrops are only known in central Cuba, but it is also recorded in deep wells from Havana to Matanzas Province. The Camajuaní TSU outcrops as an Upper Jurassic–Cretaceous belt, about 1200 m thick, of well-stratified carbonates (including turbidites), partially derived from the erosion of the coeval Remedios bank and, in part, fed by hemi-pelagic deposits, including some chert. As it occurs with the Remedios bank, the Turonian–Maastrichtian hiatus is also present. An inlier of shallow water Cretaceous carbonates (Gibara Formation) is present near the homonym city.

The Placetas TSU is known from outcrops and wells from eastern La Habana to Camagüey Province, in eastcentral Cuba. The Tithonian–Cretaceous stratigraphy of the 1300–1700-m-thick Placetas belt is very similar to those in the SR-APN-E unit of the Guaniguanico Mountains [109, 30]. However, in the oldest strata, instead of the thick siliciclastic deltaic succession, a thin shallow upper Oxfordian marine arkosic interval rests below the Tithonian–Cretaceous beds. The arkosic strata (Constancia and Quemadito formations) lie above a paleoregolith containing marble and granitic clasts. Pszczolkowski and Myczynski [109] suggest that the granites (with Jurassic radiometric ages) were torn off from the Proterozoic basement (marbles). The structure of Placetas TSU is very similar to those in SR-APN-E unit. Together, the arkosic strata and the phlogopite marbles are thrust slices caught between Placetas TSU rocks [101]. In the northern Camaguey Province, the lowermost beds of the TSU are a Tithonian sequence with basalts and limestones [55].

It is a remarkable fact that the outstanding similarities between the geological settings of the above studied NAP in northcentral Cuba and the coastal Belize Cretaceous section report by Schafhauser et al. [118] and their relationships with the corresponding neighboring ophiolites and Cretaceous volcanic arc sections. This is a key item for understanding the regional Mesoamerican geology that must be studied in the near future.

Several peculiar deposits related to the asteroid impact at the Cretaceous/Paleogene boundary (the Cacarajícara, Moncada, and Amaro formations) occupy the uppermost NAP. We will return later on this subject.

The North American Paleomargin in easternmost Cuba (Maisí). Dark-colored marbles and metaterrigenous rocks in the eastern tip of Cuba are exposed in Maisí (Fig. 5.1, Asunción complex of [59], see also [122, 26, 27, 81]. The lowermost beds are phyllites and slates, with some marbles and metamaphytes (Sierra Verde Formation), very similar to the metaterrigenous Jurassic beds in western and central Cuba. Above, resting with tectonic contact [27] lies Upper Jurassic marbles and calcareous schists (the Chafarina or Asunción Formation) probably of Upper Jurassic age. KVAT and NOB rocks apparently rest on this small North American paleomargin outlier [81].

5.3.2.2 The Northern Ophiolitic Belt (NOB)

The ophiolitic association is a record of the oceanic lithosphere rocks, emplaced by tectonic processes upon the continental or island arc margins. The Cuban ophiolites belong to the Mesozoic basement. However, some of them were remobilized during the early Paleogene Cuban orogeny and even later been emplaced together with lower Cenozoic rocks. Three different ophiolites can be recognized in Cuba [18]:

- The Northern ophiolitic belt.
- The metamorphic basement of the KVAT [82].
- Tectonic slices in the central Cuba Guamuhaya (Escambray) metamorphic terrane.

The last two units will be visited later, related to the Cretaceous volcanic arcs and the Southern Metamorphic Terranes. More than 90% of the oceanic lithosphere remains in Cuba are included in an almost continuous belt of strongly deformed rocks, northward transported over the NAP during several tectonic events. The NOB (Fig. 5.1) encroaches about 5–6% of Cuba's surface. As in other ophiolite belts, several members of the oceanic lithosphere are present: (a) the ultramafic tectonites, (b) the stratified mafic and ultramafic, (c) the massive gabbros, (d) the diabase complex, and (e) the vulcanogene-sedimentary member (Fig. 5.7). The NOB is essentially a huge mélange (Fig. 5.8), stretching circa 1000 km along the northern half of Cuba, with blocks mainly formed by lithologies of the ophiolitic association (mafic and ultramafic rocks) embedded in a strongly deformed serpentinitic matrix that flows during deformation. This superposed structures strongly mask the original contacts, mixing, crushing, and deforming, not only the ophiolite members, but also their country rocks [18].

Different tectonic settings occur along the strike of the NOB. From west to east, the following main outcrops occur Fig. 5.1: (1) Cajalbana–Bahia Honda,(2) Havana–Matanzas; (3) Villa Clara; (4) Camagüey; (5) Maniabón Highlands; and (6) Mayarí–Baracoa Highlands [18, 38]. Additionally, a peculiar isolated outcrop of brecciated serpentinites near the Caribbean coast in Guantánamo Province reveals the youngest ophiolite emplacement identified in Cuba [18, 23].

Fig. 5.7 Thin bedded chert and shales (dark rocks in the photo) in the vulcanogene-sedimentary member of the western Cuba ophiolites (Encrucijada Formation), south of Bahia Honda, Artemisa. Below, and probably in tectonic contact, rest deeply weathered basalts

Fig. 5.8 Vulcano-serpentinitic mélange at Loma Esmeralda, Matanzas Province. Serpentinite (S), strongly brecciated and with slickensides, contact with tuffs (T)

Few robust age data are known from the NOB rocks: Tithonian, Hauterivian–Barremian, and Aptian–Albian fossils have been reported in sedimentary interbeds [3, 76], whereas K–Ar radiometric ages range from 126 to 52 My [60]. The Early Cretaceous radiometric ages are in a general good agreement with the stratigraphic data, whereas Late Cretaceous–Paleogene radiometric ages record tectonic or thermal events in the most "fortunate" examples. The sum of the geological, geochemical, and petrological data suggests that the NOB rocks probably originated in two distinct tectonic environments [18]:

– as part of the Tethys oceanic basin, from Late Jurassic to Early Cretaceous, during Pangea breakup and later separation of the North and South American plates.
– in an Aptian–Albian Backarc Basin, related to the lower Cretaceous KVAT.

In the next paragraphs, we will briefly discuss how and when the different NOB sectors arrived to their present locations. The oldest ages reported from the NOB are Upper Jurassic. This was the time of the breakup of westernmost Pangea, when the North American plate began its splitting from neighboring continents. Oxfordian, Tithonian, and Berriasian fissure tholeitic magmatism in western and central Cuba [14, 15, 18, 55, 56, 107, 108] support this interpretation. Therefore, it seems likely that a first oceanic lithosphere was created from Late Jurassic to Early Cretaceous (Neocomian) as part of the Tethys Ocean south of the Mesozoic North American margin, as a consequence of the North American/Gondwana separation (see Fig. 14 in [18]).

As we will see, the youngest NOB rocks coeval with the oldest KVA representants, which grew from an oceanic basement, during Aptian–Albian time. According to plate tectonic models, Backarc Basins often develop behind volcanic arcs, and geochemical data suggest that part of the NOB lithologies show such suprasubduction signatures [66]. As convincing evidences of Upper Cretaceous ophiolites in Cuba have not been found, we can suppose that the generation of oceanic lithosphere in the Backarc Basin ended in the Albian (see Fig. 16 in [18]). Some remarkable changes in the rock composition of the KVAT occur in the transit from the Lower to Upper Cretaceous. The most significant is the change to a dominant calcoalkaline signature. This feature is accompanied with frequent volcanoclastic sedimentary interbeds. Some geologists consider that these changes could be related to a change in subduction polarity [32]. After that event, three main tectonic emplacement events can be discriminated in the Cuban ophiolite massifs:

- The late Campanian event.
- The Maastrichtian event.
- The early Paleogene Cuban orogeny.

Additionally, a brief Middle or Late Eocene local emplacement episode, related to the opening of the Cayman Trough, has been identified [18].

The Campanian emplacement event. The abundant Upper Cretaceous volcanic and intrusive rocks, mainly with calcoalkaline signature, but some with a significant alcalic trend, together with some tholeites, and frequent volcanoclastic sedimentary interbeds, points to the development of a second Cenomian to Campanian volcanic arc, more or less parallel to the North American Mesozoic [18]. The simultaneous end of volcanism along all the Late Cretaceous arc during the Campanian suggests that subduction stopped. Several evidences mark a coeval episode of ophiolite emplacement, possibly related to the closing of a small oceanic remnant basin, located between the arc and the North American Mesozoic margin (see Fig. 15 in [18]). Preceding this event, for the first time in its Cretaceous history, to the southeastern North American margin arrived volcanoclastic sediments. This fact could be possible only if the remnant basin was closed at the Campanian decline. In western and central Cuba (from Artemisa to Las Tunas Province), Campanian and/or Maastrichtian terrigenous beds, frequently with isolated serpentinitic clasts, lie on the serpentinites or gabbroids. This unconformity testifies about a major Campanian orogenic event [17, 105, 106]. The isolated clasts of ophiolitic origin in several localities can be explained by minor obduction events from near surface bodies. A coherent explanation to the preceding facts is that the remaining oceanic lithosphere between the Late Cretaceous volcanic arc and the Mesozoic North American Mesozoic margin was finally subducted during the late Campanian and, these formerly isolated tectonic units, juxtaposed (see Fig. 14b in [18]). This episode is concealed by the thrusting related to the early Paleogene Cuban orogeny. However, it was an arc/continent collision, accreting the Paleo-Caribbean oceanic Mesozoic lithosphere plus the Cretaceous volcanic arc terrane, to the North American plate [18]. Such outstanding collision is not included in the most popular regional tectonics versions ([91, 61, 66], and others).

The Maastrichtian emplacement events. These are two remarkable events in the NOB history. Whereas the late Campanian event probably embraces all Cuba, and the Paleocene–Middle Eocene event most of its territory, the Maastrichtian one is limited to two regions in eastern Cuba, where the ophiolite emplacement followed different paths.

The first area contains the NE Cuba Highlands, from Sierra de Nipe to Moa-Baracoa Mountains (Fig. 5.9) where, in several places below the huge horizontal lying ophiolite massifs, rest lenticular Maastrichtian olistostromic deposits (La Picota Formation), attaining tens to hundreds meters thick (Fig. 13 in [23]). The massive chaotic nature, monotonous composition (almost all the clasts belong to the ophiolitic suite) and poor rounding tell us that the ophiolite obduction was an intense and violent process The huge ophiolitic bodies arrived to the Earth's surface in a marine environment and spread, following the regional slope of the sea floor (possibly northward) sliding upon the olistostromic carpet, crushing and pushing it at velocities of ten millimeters per year. The displacement attained, at least, 30 km (probably no least than 60 km in Moa–Baracoa highlands) [12, 21, 18].

The second Maastrichtian episode is recorded at the Maniabón Highlands, in the NW part of the Holguin

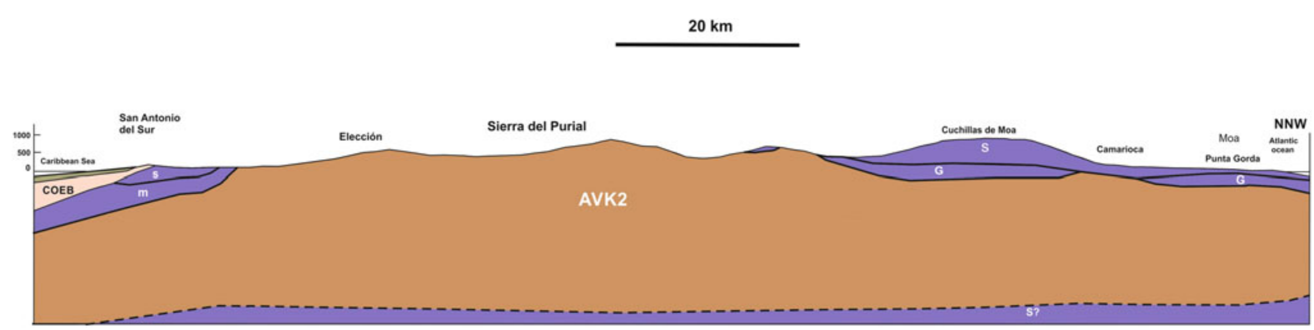

Fig. 5.9 Profile located near the eastern end of Cuba, from San Antonio del Sur, in the Caribbean coast, to Moa, in the Atlantic shore. NOB: G-gabbroids, S: serpentinites, and serpentinized ultramafic rocks, m-melánges. The KVAT is represented by Upper Cretaceous metavolcanics and some metasediments (the Sierra del Purial complex). It probably rests horizontally sandwiched between the ophiolites

Province. The Maniabón Massif consists of anastomosing bands of strongly deformed ophiolites gently convex to the ESE, separated by south-dipping thrust faults of the intervening strongly deformed terrigenous and volcanic rocks "intercalations" (the Iberia Formation, [69, 71]). According to Andó et al. [3] much of "Iberia Formation" are severely deformed greywackes (mélange) probably settled in a fore-arc. The ophiolites are mainly foliated and brecciated serpentinites. The other members of the ophiolite suite appear as disseminated blocks included in the serpentinites. The relationships among the Maastrichtian events are unclear. Broad Cenozoic outcrops and the wide Nipe Bay separate both regions [110].

Ophiolite emplacement during the Cuban orogeny. This is the last major event affecting the NOB [18, 23, 46, 47, 68, 106]. The deformation developed by steps, in blocks bounded by NE-SW sinestral strike-slip faults. Again, coeval with the ophiolite emplacement olistostromes accumulated. However, in this case, besides serpentinite and other members torn from the ophiolite suite, abundant debris flows with blocks derived from the Mesozoic NAP and the KVAT accumulated on the fast subsiding foreland basin located in front of the northward moving thrust sheets. The structural and stratigraphic evidences indicate that, in the Early Paleogene, those part of the NOB located westward of the Cauto-Nipe lineament traveled northward, together with the Cretaceous volcanic arc, riding the NAP and its overlying foreland basin. Huge wedges, but also thin scales of the well-stratified Jurassic and Cretaceous Placetas TSU were detached, scoured, imbricated, and deformed together with the ophiolitic rocks and the Paleogene olistostrome. In many places, this process conduit to melánge formation ([16], Fig. 5.8).

Meanwhile, the Cuban orogeny, as a whole, extends from middle Paleocene to Middle or Late Eocene, and it doesn't operate simultaneously all along the NOB. During the orogenic event, thrusting migrated progressively eastward along fault-bounded blocks or sectors. In each sector, the orogenic event was a relatively short-lived process. In the western block, flanked by the Yabre lineament, deformations extend from Middle Paleocene to Early Eocene. In the central block, located between La Trocha fault zone and Yabre lineament, folding and thrusting attain the Middle Eocene, and eastward of the last dislocation the orogenic event concluded during the late Middle Eocene or early Late Eocene (see [18], Fig. 16). It is a fundamental item in the interpretation of the tectonics of Cuba to define if there was an ophiolite obduction related to the Cuban orogeny. This will be discussed at item Sect. 5.3.4.

Field and well data indicate horizontal displacements of the NOB attaining several ten kilometers in the most conservative estimations [18, 19, 23, 20, 108, 117].

5.3.2.3 The Cretaceous Volcanic Arc Terrane

In the pre-Plate Tectonics geological literature on Cuba, those geological sections containing Cretaceous volcanic rocks, serpentinites, and igneous Mesozoic rocks, together with the Paleogene foreland and piggyback deposits and, in some schemes, even the Paleogene volcanic arc were referred as the eugeosyncline and included in the classical regional schemes of the 1950 and 1960s. Several oil geologists proposed different local names for the "Cuban eugeosyncline" ([33, 46], and others). The most popular was the "Zaza zone," even used today by some geologists (the Zaza TSU, [75]). However, if we intent to explain the geology of Cuba in plate tectonics terms, the "Zaza zone" is an obsolete concept, because it mingles rocks of very different origins: the ophiolite suite, the KVAT (Fig. 5.1), including its Campanian–Maastrichtian cover, plus some volcanomictic Paleogene successions.

By its volume, the KVAT is the main component of the Mesozoic basement. It's composed of volcanic arc rocks, with more or less outstanding sedimentary interbeds [91]. Intrusive bodies frequently cut the supracrustal rocks. An upper Campanian–Maastrichtian cover unconformably rests on the older rocks. Except in the eastern Cuba outcrops, it rests mainly with tectonic contacts upon the NOB. However, in the great festers of the Isla de la Juventud and Guamuhaya (Escambray) Mountains, the Southern Metamorphic Terranes outcrop below it [110]. The tectonic nature of its basal contact and the lack of stratigraphic contacts with the pre-Maastrichtian rocks of the other Mesozoic basement units allow to consider the KVAT as a tectono-stratigraphic terrane.

Most of the Cretaceous volcano-sedimentary sections lie below hundred to thousand meters of sedimentary Cenozoic rocks in the southern half of Cuba, except in SE Cuba, where the Paleogene volcanic arc developed above the KVAT [110]. Along its strike, the KVAT structure, rock composition, and age modified. The maximum complexity is attained in central Cuba, between the Yabre lineament and La Trocha fault zone. East and westward, the terrane becomes thinner and less varied. Around the Guamuhaya tectonic window (where the SMT outcrops) the following KVAT tectonic assemblage is present (from lower to upper members):

– Mabujina complex: a metamorphic complex mainly built up from mafic protoliths transformed into amphibolites, with a high temperature/pressure ratio. Most of the protoliths belong to a supposed Mesozoic ophiolite basement; however, the complex also includes calcoalcalic rocks derived from the lowest levels of the KVAT [82, 86]. Several deformational events are recorded in the Mabujina complex rocks and three metamorphic zones (all included in the amphibolite facies). The radiometric age data, mainly from K–Ar datation, yield Upper Cretaceous ages, [59]. A U–Pb age in zircons from gneissiod granitoids yields 132 My.

In tectonic contact with the Mabujina complex appears a volcanic non-metamorphosed sequence; 1000–3000-m-thick pile of felsic and mafic rocks (Los Pasos Formation), with some andesite and sandstone intercalations. Abundant subvolcanic bodies and some ignimbritoid rocks point to some subaerial volcanism. However, most of the beds accumulated on submarine settings as a consequence of central and fissure volcanic activity. The petrographic composition is very similar to the Primitive Island Arc suite but geochemical data are insufficient for a robust definition. This bimodal suite is very similar to the Lower Cretaceous Los Ranchos Formation in Dominican Republic [37]. Probably above Los Pasos Formation lie basaltic and andesitic lava flows and tuff beds with marine sedimentary interbeds, conforming a 4000-m-thick packet of calcoalkaline and tholeitic rocks (Mataguá Formation—[34]), of Aptian–Albian age. Vertical and laterally the Mataguá Formation transits to Albian andesitic and felsic tuffs and tuffites with sandstones and andesitic and dacitic lavas (Cabaiguán Formation), 1000–3500 m thick. Thinner Lower Cretaceous andesitic and basaltic tuffs, with some mafic sills and dykes (Chirino Formation), are also recorded in La Habana, Mayabeque, and Matanzas Provinces [110].

A concordant, mainly sedimentary Albian–lower Cenomanian section, with terrigenous and carbonate turbidites (Provincial Formation), covers the Lower Cretaceous beds in central Cuba. Some tuffaceous strata testified about isolated explosive eruptions, whereas shallow carbonates in Cienfuegos Province record coeval banks and a widespread volcanic recess. However, the absence of a widespread unconformity, some local deformations are recorded in central Cuba [17] whereas the petrological features and geological setting of the Upper Cretaceous beds suffer drastic changes. This points to a major tectonic event yet not enough recognized [17].

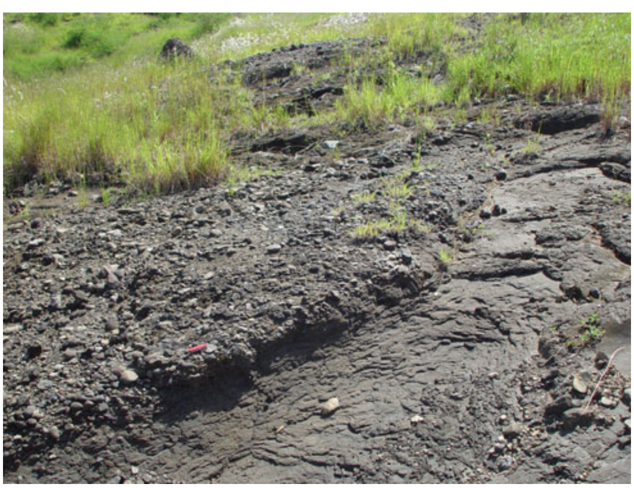

Fig. 5.10 Upper Cretaceous conglomeratic and sandstone beds of La Trampa Formation, eastward Havana city. These sediments show that, contrary to the events in the Early Cretaceous, in the Late Cretaceous volcanic arc, some volcanic cones suffer the subaerial erosion

The overlying volcano-sedimentary Upper Cretaceous section possesses several remarkable features, clearly separating it from the underlying Lower Cretaceous arc:

- In contrast with the tholeitic or tholeitic-calcoalkaline underlying rocks, the Upper Cretaceous magmatic rocks mainly belong to the calcoalkaline suite, sometime with a marked alkaline trend. Only in the NE Cuba Highlands, tholeitic rocks are present [58].
- Volcanomictic interbeds are abundant (Fig. 5.10), pointing clearly to important subaerial volcanic buildings (islands) and erosion [34].
- Whereas the Lower Cretaceous rocks are limited to a discontinuous belt from La Habana to central Camaguey, the Upper Cretaceous volcanic rocks are recognized in outcrops and subsurface all along Cuba.
- The thickness of the volcano-sedimentary Upper Cretaceous section in western Cuba is only of several hundred meters, in central Cuba perhaps attains a maximum thickness of 2000–3000 m, in Camaguey–Las Tunas territory is poorly defined—probably several thousand meters [62, 96].
- A variable volcanic activity is represented in the Upper Cretaceous rocks. Fissure magmatism was active in some localities of western and central Cuba, whereas structures of central volcanism have been identified in eastern Camagüey and Las Tunas Provinces [36]. Coeval intrusive magmatism in the KVAT eastern half is indicated by abundant stratigraphic and radiometric data [61].

In the Maniabón Highlands, an extremely complicated area contains a mélange where the NOB and the KVAT are intimately mingled [3]. The KVAT form narrow, arcuate strips, gently convex toward the SE, alternating with lenses of pervasively crushed and foliated serpentinites. Two kinds of serpentinitic-volcanic mélange coexist. The most widespread is the Iberia mélange, with crushed and foliated basaltic and andesitic rocks and their tuffs and sedimentary packets. The second mélange is the "Loma Blanca Formation," rich in felsic tuffs, often zeolitized. Serpentinitic clasts are abundant in both units.

Contrary to western and central Cuba in the highlands of eastern Cuba (Sierra de Nipe, Sierra Cristal and Moa-Baracoa massif), the Upper Cretaceous volcanic arc rocks lie below the NOB [69], tectonically emplaced during the Maastrichtian [12, 23, 60, 61, 57]. Four lithostratigraphic units (the Santo Domingo, Téneme, Morell, and Quibiján Formations) have been distinguished [58]. Except the youngest one (Santo Domingo), the other formations contain Turonian to Coniacian basaltic rocks. The Santo Domingo Formation (Santonian to Campanian) contains andesitic tuffs, with some sills. All these units rest below the large ophiolitic massif of eastern Cuba. Excellent examples of this relationship are the great fenster of the Téneme and Cabonico River Valleys in northern Sierra Cristal [69, 110] and the Mayarí River Valley at Sabanilla, Mayarí Arriba [12]. The third area of Upper Cretaceous volcanic arc rocks is the Sierra del Purial Mountains, located near the eastern tip of the island. In this region, metavolcanic rocks (green and blue schists) of calcoalkaline to tholeitic signature [26, 81, 84]) with some intercalated marbles (Sierra del Purial Formation) record the only metamorphic rocks in the Upper Cretaceous arc. These rocks were sandwiched between the NOB (above) and the NAP Mesozoic metamorphic rocks during the Maastrichtian ophiolite emplacement [122, 26, 58].

The higher structural stage of the KVAT, the Campanian–Maastrichtian cover, is separated from the underlying rocks by a major unconformity. The lower beds are mainly siliciclastics volcanomictic turbidites, sometime with disseminated serpentinite grains. These beds can attain thickness up to several hundred meters. Carbonate lithostratigraphic units (Cantabria, Jimaguayú, Tinajita Formations, and others) tend to occupy the highest stratigraphic positions with thickness from ten to some hundred meters. From Pinar del Rio to Matanzas Provinces, the younger beds of the cover belong to Peñalver Formation, an extraordinary clastic deposit, with abundant spherules, grains of shocked quartz, and other particles, typically related to asteroid impacts [126]. In central Cuba, coeval deposits are known in the Santa Clara Basin (see Sect. 5.3.2.4).

5.3.2.4 The Cretaceous/Paleogene Boundary Event Deposits and Paleogeography in Western and Central Cuba

Several types of extraordinary Cretaceous/Paleogene boundary sediments, with sharp differences in composition and thickness, are widely distributed in western and central Cuba, 500–1000 km eastward from Chicxulub crater in Yucatan: Cacarajícara, Amaro, and Moncada Formations and the DSDP 536 and 540 sites rest on the North American Mesozoic paleomargin, whereas Peñalver Formation and a section of K/Pg deposits, included in the central Cuba Santa Clara Formation, lie on piggyback basins, developed upon the extinct Cuban Cretaceous volcanic arc Fig. 5.11, [2, 20, 44, 102, 126].

According to Cobiella Reguera et al. [20], three types of deposits are present. Type 1 (Cacarajícara, Amaro, and Peñalver Formations) presents in its lower part thick gravity flow accumulations, followed by graded massive finer calcareous debris (homogenite). The depositional area of Cacarajícara plus Amaro formations was circa 25,000 km^2, with estimated original sediment volume of 2500 km^3. For Peñalver Formation, with about 17,500 km^2 of depositional area, gross volume estimates give 1750 km^3 of original sediments. Type 2 (K/Pg deposits in Santa Clara Formation and DSDP sites also contain gravity flow deposits in their lower part, but instead the homogenite, ejecta-rich deposits are present. Type 3 mainly contains reworked ejecta clasts (Moncada Formation). Some features in the deposits can be

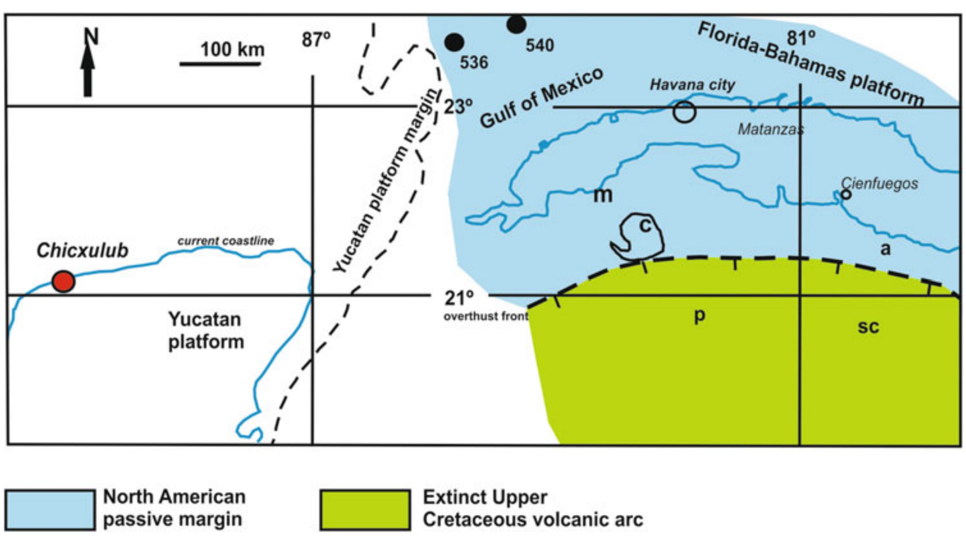

Fig. 5.11 Palinspastic reconstruction of the NW Caribbean–SW Gulf of Mexico region surrounding western and central Cuba at the Mesozoic/Cenozoic boundary (for details consult [20]). m: original area of Moncada-type deposits, c: original area of Cacarajícara-type deposits, a: original area of Amaro-type deposits, p: original area of Peñalver-type deposits, sc: original area of Santa Clara-type deposits

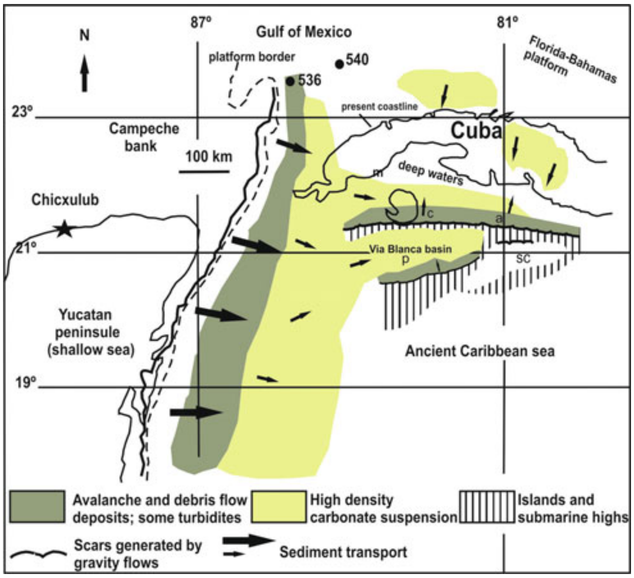

Fig. 5.12 Paleogeographic scheme at the Cretaceous/Paleogene boundary. Observe the complex regional relief in the area of the future western and central Cuba at the moment of the Chicxulub impact [20] modified from . m: original area of Moncada-type deposits, c: original area of Cacarajícara-type deposits, a: original area of Amaro-type deposits, p: original area of Peñalver-type deposits, sc: original area of Santa Clara-type deposits

explained by the travel of several mega tsunami waves during their deposition. A clear zonation of K/Pg boundary beds is present in the Gulf of Mexico. Accumulations similar to Type 1 beds (but without or with poorly developed homogenite equivalents) settled in the northern and southwestern fringes of Yucatan Peninsula, whereas thin-bedded siliciclastic ejecta-rich strata extend northward in the circum-Gulf areas.

The Cretaceous/Paleogene boundary sediments in western and central Cuba record the event chronology related to the asteroid impact in an original area of approximately 90,000 km^2, 500–1000 km east to southeastward of the Chicxulub impact crater. Compared with coeval sediments in other areas of the world, the Cuban K/Pg beds show extreme changes in thickness and composition in short distances, pointing to a complex geography in the northwestern Caribbean, 65,5 My ago (Fig. 5.12). Additionally, some erosion of the underlying beds by currents during the event is recorded in many places, complicating the interpretation of the latest Maastrichtian paleogeography. Finally, the original sediment distribution was severely distorted by the early Paleogene orogenic events in Cuba.

According to different sources, the northward thrusting for distinct tectonic units in western Cuba ranges between 12 and 200 km [19, 108, 117]. Therefore, in order to restore the original K/Pg boundary sediment distribution and the paleogeography of the northwestern Caribbean corner at the time of the asteroid impact, a combination of Palinspastic reconstruction and sedimentological research of such deposits and the underlying upper Maastrichtian and overlying lower Danian beds was necessary [19, 20].

5.3.2.5 The Southern Metamorphic Terranes (SMT)

Iturralde Vinent, in 1996, proposed to distinguish the metamorphic massif of southern Cuba (Isla de la Juventud and Guamuhaya or Escambray) and the Mesozoic sections of western Cuba (Guaniguanico Mountains) as tectonic terranes and named them "The Southwestern terranes." According to Keppie's definition (in [17]), a terrane is "an area characterized by an internal continuity in geology that is bounded by faults, mélanges or a cryptic suture across which neighboring terranes may have a distinct geological not explicable by facies changes or a similar geological record that is bounded by faults, mélanges or a cryptic suture… that may only be distinguished by the presence of the terrane boundary representing telescoped oceanic lithosphere." Initially, several authors followed Iturralde Vinent's proposal ([61, 91, 108], and others). However, Cobiella Reguera [22, 17, 18, 22], and Pszczolkowski and Myczynski [109] questioned the idea. In the current paper, the author only considers as terranes of continental origin in Cuba, the Pinos (Isla de la Juventud) and Guamuhaya terranes. In both areas, the protoliths are of Mesozoic age, and with remarkable similarities, in stratigraphic architecture and age, to the Guaniguanico sequences of western Cuba. Consequently, they are here classified as "proximal terranes."

Most of the Isla de la Juventud (IY in Fig. 5.1) consists of metasedimentary rocks. The lower part of the section contains quartzose graphitic metapelites and metapsamites (Cañada Formation). These lithologies continue in the middle part but with increasing quantities of marbles and calc-silicate beds (Agua Santa Formation). The upper strata consist almost entirely of gray and black dolomitic marbles (the Gerona Group). A Jurassic age for the protolith of the last beds is suggested by the discovery of some cephalopods and foraminifera [84]. Some amphibolites (possibly from a magmatic protolith) are present in Gerona beds. The metamorphism is HT/MP type. Six metamorphic zones were recognized by Millán Trujillo [85], which are (from lower to from lower to higher degree): (1) greenschist, (2) estaurolite/kyanite/garnet (low degree amphibolite), (3) estaurolite/Kyanite (occasional andalusite), (4) garnet/kyanite/biotite; (5) sillimanite/garnet/K feldspar (sillimanitic gneiss); and (6) migmatites.

An elliptical dome, developed in an extensional environment, embraces all the Isle. Extended fracturing of the metamorphic rocks was accompanied by felsic intrusive magmatism and wolfram mineralization. The scarce radiometric data (K–Ar) yield 78–72 My ages for the metamorphites (late Campanian). In a subvolcanic non-metamorphosed body intruding the metamorphic massif, a 78–72 My radiometric age (Campanian) was recorded.

Meanwhile, some nappes are recognized in the Isla de la Juventud Massif, compared with the tectonic setting of Guamuhaya Massif, they are few. This situation probably is related to the absence of serpentinites and mélanges, abundant in the central Cuba Millán Trujillo [86] distinguishes four major regional structures, supported on the lithology and trends of the main foliation: Nueva Gerona and San Juan sinforms and Rio Los Indios and Guayabo antiforms (Fig. 1 in [85]). All the contacts between them are tectonic.

In the Guamuhaya tectonic window, the older rocks are also metaterrigenous beds, but here accompanied by concordant metamafic bodies (La Llamagua, La Chispa, Loma La Gloria, and Herradura Formations). Above rests a metaterrigenous-carbonate interval, followed by marbles with a few Upper Jurassic fossils (San Juan Group, Millán and Myczynski 1978, 1979). Therefore, the general stratigraphic picture is quite similar to those in the Isla de la Juventud and Guaniguanico Mountains, especially to the Sierra del Rosario-Alturas de Pizarras del Norte-Esperanza unit. However, whereas Cretaceous rocks are unknown in the Isla de la Juventud (Isle of Youth) Massif, in the Guamuhaya Mountains the metavulcanogen-sedimentary section structurally above the Jurassic marbles is probably Cretaceous (Los Cedros, La Sabina, Loma Quibicán, Yaguanabo, and El Tambor Formations [86]). Radiometric (K–Ar) ages in the southcentral Cuba metamorphic massif yield mainly Upper Cretaceous ages [86]. In zircons from eclogitic rocks using the U–Pb method, ages from 106 to 102 My have been obtained.

The Guamuhaya Massif (Fig. 5.1) forms two large dome-shaped structures, the Trinidad (west) and Sancti Spiritus cupolas well marked in relief and separated by the Agabama Valley (or the Trinidad Basin, in a tectonic approachment). The dome is also reflected in the KVAT rocks, as is visible in regional geologic or tectonic maps. The age of the Cretaceous arc emplacement is Late Cretaceous, since a basal slip plane (*decollement*) affects the Upper Cretaceous arc rocks but not its Campanian–Maastrichtian cover. Additionally in the Guamuhaya (Escambray terrane), the tectonic contact with the overlying KVAT is crossed by 88–80 My old pegmatites [124] Then, the precedent facts show that the terrane welding in central Cuba seems a Pre-Coniacian event. Millán Trujillo [86] considers that this event was simultaneous with the greenschist facies metamorphism recorded throughout the massif. This same author distinguishes four major tectonic packets ("Main Tectonic Units," MTU). The lowest one is the first MTU and the fourth is the highest. Each MTU is divided into smaller nappes. The first and second MTU are the lower units and the third and fourth the higher ones. The Guamuhaya Massif has a high-pressure metamorphism, with an inverted zonality from the first to the third nappe. The metamorphic peak is reached in the third unit, which records pressure/temperature 15–23 kbar/470–630 °C [124]. The fourth MTU contains rocks metamorphosed under lower temperatures than the third. A subsequent event of greenschist metamorphism affects the whole massif. According to Millán Trujillo [86], the first metamorphic event occurs circa 106–100 My ago (Albian). Contrary to the Pinos terrane, in Guamuhaya Mountains, abundant serpentinite and metamafic bodies are tectonically included or were originally emplaced as magmatic bodies, later metamorphosed together with the sedimentary country rocks [86]. The most remarkable of them are the high-pressure amphibolites of the Yayabo Formation (12–14 kbar/550–580 °C). Probably originally they were part of the Lower Cretaceous volcanic arc, tectonically mixed with the Guamuhaya metamorphites [124]. In our opinion, other metamaphytes, not spatially linked with serpentines (e.g., the Felicidades Schists), could be manifestations of continental margin magmatism, similar to that recorded in the Jurassic beds at Guaniguanico Mountains [14, 107].

A recent study by Despaigne Díaz et al. [31] concludes that the rocks in the Trinidad dome suffered a Late Cretaceous (circa 75 My)–Paleogene (circa 50 My) subduction-exhumation event, with five main episodes (D1–D5). This contradicts all previous results that consider the metamorphic events in Guamuhaya as Cretaceous. In our opinion, the interpretation of the $^{40}Ar/^{39}Ar$ data by the authors is confusing, because of the abundant overlap between D1 and D3 values (all with very similar Paleocene radiometric ages that suggest an overprint derived from the Cuban orogeny events).

The first clasts of metamorphic rocks in the sedimentary basins surrounding Guamuhaya (Escambray) Mountains appear in the Middle Eocene beds [86]. However, Stanek et al. [124] consider that exhumation of the Mesozoic metamorphic complex began about 70 My ago, during the Maastrichtian. The Cenozoic stratigraphic record and the current relief indicate that uplift still continues today (see later).

5.3.3 The Paleogene Folded and Thrusted Belt

The KVAT-UK cover unconformity, together with the tectonic burial of the SMT below the Cretaceous volcanic arc, reveals the arc collision with the North American plate border. This event forced the end of the arc and the reconstruction of the plate boundaries in the early Paleocene. In this complex setting, the following new Early–Middle Paleogene structures are recognized:

- The Early–Middle Paleogene Foreland Basin (PFB).
- The piggyback basins (PBB).
- The Turquino–Cayman Ridge volcanic arc (T-CR).
- The central Oriente intramountainous Eocene Basin (COEB).

5.3.3.1 The Early–Middle Paleogene Foreland Basin

Along northern Cuba, from Pinar del Rio to NW Holguin Province, the Mesozoic NAP is covered by the siliciclastic deposits of a foreland basin. These successions accumulated in front of the thick nappe pile were generated during the early Paleogene Cuban orogeny, as a result of the erosion at the frontal thrust region and the intensive basin subsidence due to the weight of the nappe building. This process creates the space for the accumulation of large volumes of deposits (Fig. 5.13). Therefore, sedimentation is coincident with the orogenic deformation [63]. In the basin, a tight imbrication exists between (a) the debris flows (olistostromes) and turbidites derived from the erosion of the tectonic pile and (b) the southern thin tectonic wedges derived from the Mesozoic basement (ophiolites, KVAT, and the NAP). Northward of this deformed strip, the crust was progressively depressed as the basin developed and the nappes of the Mesozoic basement overrode, crushed and partly mingled with the chaotic breccias, creating mélanges (Fig. 5.14). With time, the Cuban orogeny events migrated eastward. In western Cuba, it developed from late Paleocene to Early Eocene. In this sector, the sediments are mostly chaotic, with clasts from the different units of the Mesozoic basement (except the Southern Metamorphic Terranes). West of La Habana they are known as “Manacas Formation” [16, 97], and lie sandwiched between the Mesozoic units of the Cordillera de Guaniguanico. Eastward from La Habana, the northern sub-basin fill conforms tectonic lenses in between the well-stratified strata of the Placetas TSU, known here as the “Vega Alta Formation.”

Between the Yabre lineament and the La Trocha fault zone the tectonic event occurs from the Paleocene to Early Eocene. In this sector, the foreland basin shows two different outcrops (or sub-basins). The southern one contains crushed chaotic olistostromes of the Vega Alta Formation type (Paleocene to Middle Eocene age), with clasts derived from the Placetas TSU and the ophiolite association. In the northern sub-basin, the chaotic deposits (Vega Formation) only contain clasts from the Camajuaní and Remedios TSU. Between La Trocha FZ and Camagüey lineament, the southern foreland sub-basin basement belongs to the Remedios TSU, whereas the depression fills with chaotic sediments, eroded from the ophiolitic association and, in lesser degree, from the Placetas TSU and the KVAT, known as the Senado Formation. The formation is circa 1000 m thick. The external (northern) sub-basin filled with clastic carbonate sediments, torn from the Lower–Middle Eocene Florida–Bahamas platform border deposits. The presence of fine tuff interbeds in the Middle Eocene Lesca Formation is clearly related to the distal volcanic pyroclastic eruptions (probably from the Turquino–Cayman Ridge Paleogene arc. The northern sub-basin fill rests on the Cayo Coco TSU rocks.

The fourth outcrop area of the foreland basin is located around Gibara City in NW Holguin Province (Fig. 5.1). Again, two sub-basins can be distinguished with different

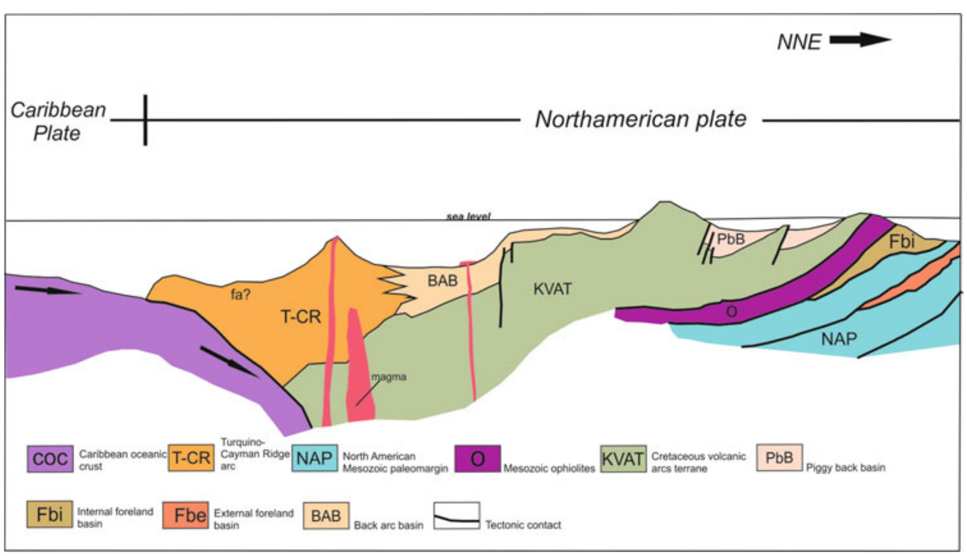

Fig. 5.13 Early Paleogene tectonic profile across central Cuba, including the Turquino–Cayman Ridge arc, in its southern edge to the foreland basin, in the north

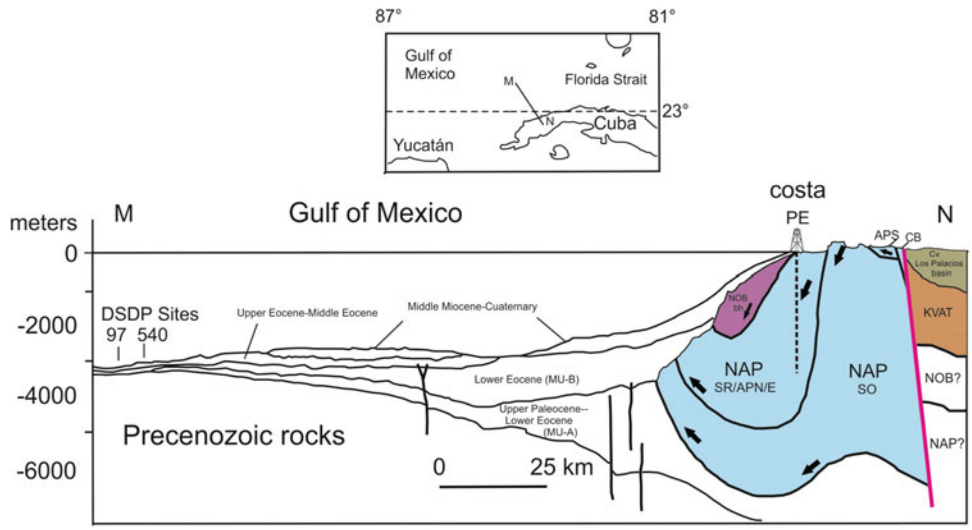

Fig. 5.14 Profile from Los Palacios Basin to the DSDP sites 97 and 540 in the SE Gulf of Mexico (modified from [19]). The profile integrates seismic and DSDP well data in the SE Gulf with data from inland wells and geological cartography in Pinar del Rio Province, Cuba

clastic compositions. The southern depression contains the Rancho Bravo Formation, very similar to the Senado Formation from Camagüey. The Rancho Bravo Formation [62] is in tectonic contact with the NOB and the Iberia mélange [110]. Clastic carbonates of Embarcadero and El Recreo Formations fill the northern part of the depression [41].

The northern foreland basin corresponds to the "*backarc collisional foreland basin*" in the model of Miall [79, 89], as will be briefly discussed in Sect 5.3.4.3.

5.3.3.2 The Piggyback Basins (PBB)

Small depressions developed upon the back of great thrust sheets during their advancement were first recognized about 40 years ago (Ingersoll and Busby 1995) and called piggyback basins. Several of these structures, related to the Cuban orogeny, are known. Their main development is attained in central Cuba, between the Yabre and Camaguey lineaments, but several depressions of this kind are recognized in other territories. They are filled with volcanomictic deposits of limited thickness, generally resting upon the KVAT rocks (mainly on its uppermost Cretaceous cover). Less frequently these deposits rest on the NOB and then they are severely deformed, i.e., northwestward of Camagüey City. Tuffaceous interbeds are present in those basins from central and eastcentral Cuba.

In western Cuba, the Mercedes, Madruga, Apolo, and Alcazar Formations of Danian and/or Lower Eocene age belong to this kind of depression. In central Cuba, the piggyback basins attain its maximum development. Three depressions are distinguished in this region, Cienfuegos and Santa Clara, in the west and the Cabaiguán Basin, in the east. In these depocenters, the frontier between the PBB beds and the Cretaceous cover is very diffused, because sedimentation was continuous and without major lithological changes from Late Maastrichtian to Early Danian (Santa Clara Formation, [20]). Therefore, we consider these depressions as inherited PBB. It is very interesting the finding of several tuffs of Maastrichtian–Paleocene ages, evidence of a weak explosive volcanic activity in the Cabaiguán Basin. A younger, Lower–Middle Eocene volcanic explosive event is also recorded in the SE part of the same basin [64]. Other local compositional changes are present eastward. In central Camagüey, the Taguasco Formation rests upon an ophiolitic floor and it is strongly deformed. In southern Camagüey, a few kilometers southward, an increase in pyroclastic beds in the Vertientes Formation (Lower–Middle Eocene) marks the transition to the backarc basin of the Turquino–Cayman Ridge arc. Whereas, in the same province, eastward of Camagüey City, the conglomerates and sandstones, circa 250 m thick of Maraguán Formation occurs, without the report of tuffaceous interbeds. Probably they are part of the fill of a Middle Eocene piggyback basin (see Pushcharovsky et al. [110]). Finally, in the southern fringe of the Maniabón Highlands, the Haticos Formation (Upper Paleocene–Lower Eocene) contains features similar to some parts of the Taguasco Formation but, whereas in the later the clasts were derived from the denudation of a KVAT source, in the Haticos Formation ([62], Garcia Delgado and Torres Silva 1997), the clasts came mainly from outcrops of the ophiolitic suite and beds of altered tuffs are frequently interbedded. Evidently, all these particular features are related to the local composition of the clastic sources, the tectonic stresses, and the arrival (or not) of pyroclastic particles from the Turquino–Cayman Ridge arc eruptions.

5.3.3.3 The Turquino–Cayman Ridge Volcanic Arc

In the Early Paleocene (Danian), a new, almost east–west trending submarine volcanic arc was born, the Turquino–Cayman Ridge arc (T-CR), whose rocks chiefly outcrop in SE Cuba, resting on top of the KVAT (especially on its

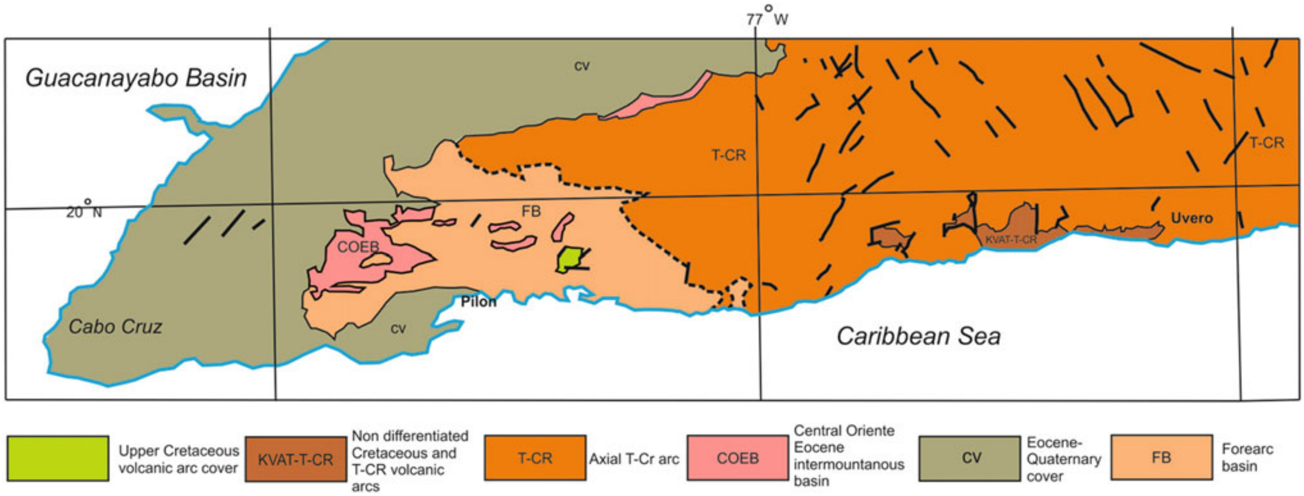

Fig. 5.15 Simplified tectonic map of the western end of the Sierra Maestra Mountains, supported on the interpretation of the Pushcharovsky [110] map and the unpublished Geological Map of Cuba from the Instituto de Geología y Paleontología [53]

Upper Cretaceous cover) and, in lesser degree, on the NOB (Fig. 5.13). Up to several thousand meters of effusive, pyroclastic, and intrusive rocks, ranging from felsic representants to basalts with sedimentary interbeds, crop out mainly in the Sierra Maestra Mountains (the old volcanic arc axis [88],Méndez Calderon et al. 1994, [60]). Its corresponding backarc basin, filled with pyroclastites, volcanogenic turbidites, and some carbonate deposits, lays to the north [13]. Effusive and intrusive bodies are scarce in the backarc. A forearc basin has not been clearly identified in the T-CR arc,however, an abrupt facies change occurs in the lower Paleogene sections, from sandstones with some volcanic interbeds (the Pilón Formation) to thick volcanogenic sections (the El Cobre Formation) at the western end of the Sierra Maestra Mountains, along a ENE tectonic contact (an overthrust or strike-slip fault) eastward from Pilón, Granma (Fig. 5.15).

Intruding along the volcanic axis rocks are a large number of igneous bodies Figs. 5.13, 5.16, ranging in composition from granite to gabbro and in structural setting from dykes and sills to stocks. According to Rojas Agramonte et al. [115], these are calcoalcalic rocks of intraoceanic origin. Pb-U radiometric ages in zircons yield ages from 60 to 48 My (Paleocene–Middle Eocene), very similar to the time span for the volcanic rocks of the T-CR. Westward, coeval volcanic beds were recorded in the Cayman Ridge and Nicaragua Plateau [50, 90]. The record of an early Paleogene volcanic arc, with a northern backarc basin, is present in the Cayman Ridge and Yucatan Basin [120]. With this architecture, a north dipping subduction zone was postulated by these authors. Coeval volcanic rocks occur in the Montaignes Noires and the Northwestern Peninsula in Haiti [8] and Sierra de Neiba in the Dominican Republic [74, 37]. Therefore, we can suspect that all these localities were originally part of an expanded T-CR arc. Probably this almost latitudinal structure was more than 1500 km long (more than the current Lesser Antilles arc) and the subducted Caribbean crust dived with a strong northward component. This was explicitly declared by Siggurdsson et al. [120], but has been largely overlooked. In many recent models on Caribbean region evolution, during the Danian to Middle Eocene interval, the oceanic crust at the leading edge of the Caribbean plate was moving E-NE [91]. In our interpretation, the lithosphere to the north of the T-CR subduction zone was already accreted to the North American plate in the Paleocene and the oceanic Caribbean crust dives below this new margin (Fig. 5.13) and the T-CR arc is essentially an in situ structure. Therefore, the great early Paleogene thrusting event along northern Cuba, from Pinar del Rio to NW Holguin Province (the Cuban orogeny), is not directly related to a supposed obduction of the Caribbean plate upon the North American paleomargin. Compare (Fig. 5.13) with the "backarc collisional foreland basin" from the model in Miall [79] and the "backarc foreland basin" in Nichols [89] (Fig. 5.16).

At the beginning of the Middle Eocene, volcanism almost ceased [13]. Perhaps it was related to the arrival at the subduction suture of a thick and less dense oceanic plateau, docking it, and immediately followed by a change in the regional stress field, with the birth of the great Oriente Fault Zone (OFZ), related to the weakened hot lithosphere of the recently extinct T-CR arc [23, 123].

The axial region of the T-CR arc presents moderate deformations. In a crude approximation, it is a huge monocline with north dipping beds, except in its eastern end, at La Gran Piedra, where the regional strike rotates toward NW–SE. Locally the monocline is complicated by folds, often related to E–W reverse folds that can be followed by several

Fig. 5.16 Basaltic columns at Puerto Moya, Central Road, Santiago de Cuba Province. The rocks belong to the middle–upper part of the axial strata of the Turquino–Cayman Ridge Paleogene arc

kilometers. In general, the structural complication decreases northward. In the Sierra Maestra, these deformations affect the Paleocene to middle Eocene beds, with a trend becoming less complicated northward. However, in the northern foothills of the Sierra Maestra, the volcanoclastic Middle–Upper Eocene beds (San Luis Formation) outcrops, conformably resting upon the underlying T-CR. Supported on this last fact, Refs. [61, 115] believe that the folding and faulting event is Oligocene in age. Dealing with the Central Oriente Eocene Basin (COEB), we will see that the San Luis Formation is related to a regional uplift event, located southward of its depocenter. The first movements along the Oriente fault zone belong to this event, as we will see in the following pages.

5.3.3.4 The Central Oriente Intramountainous Eocene Basin (COEB)

The COEB is an E–W trending synclinorium, with volcanoclastic Middle–Upper Eocene beds that extends from the eastern Guantanamo Valley up to the Sierra Maestra northern foothills, near Bayamo City, in Granma Province. The San Luis (Middle and Upper Eocene) and Camarones (Upper Eocene) Formations represent the bulk of the basin fill, meanwhile Farallón Grande and Mucaral [62, 62, 41] formations are local facies. Except for the Mucaral Formation, almost all the clastic beds were derived from the denudation of highlands located at the southern margin of the basin [27, 65, 73], built by rocks of the then recently extinct lower Paleocene–early Middle Eocene Turquino–Cayman Ridge arc. As we will see, the Central Oriente Intramountainous Basin is a key piece for the solution of some main questions on the geology of the Caribbean/North America plate boundary.

The COEB deposits (Figs. 5.17, 5.18) make a depositional wedge more than 200 km long, by circa 80 km wide (from the Caribbean coast to Sagua de Tánamo Valley), with a maximum thickness circa 800 m in the northern Sierra Maestra foothills, at Mesa de Santa Maria del Loreto Plateau. Northward of its impressive vertical cliffs, the marine coarse-grained deposits of the Camarones Formation transit toward the sandstone–siltstone turbidites of the San Luis Formation. A thickness decrease to some hundreds or tens of meters accompanies this transit at the southern slopes of Sierra de Nipe and Sierra Cristal Highlands. According to the present author interpretation of the Lewis and Straczek's [73] descriptions, probably the Middle–Upper Eocene sedimentary wedge is the sum of many submarine fans where the clastic sediments, sourced by a southern mountain range, were caught (see Fig. 18 in [23]). Keijzer [65] called this highland the "Bartlett Land." As will be seen later, this was an important discovery, not only to explain the Cuban regional geology, but also for the North American–Caribbean plate relationship. However, after 1955, it stood almost forgotten for many years [27, 25]. The Bartlett Land denudation was very active, as the granitoid clasts recorded in Camarones and San Luis Formations show. Evidently they were derived from isolated outcrops of the granitoid plutons intruding the Turquino–Cayman Ridge arc [73, 115].

Another main event recorded in the COEB is the accompanying magmatism. However, it is volumetrically insignificant, it is the youngest igneous event recognized in the Cuban territory. The intrusive magmatism is represented by andesite–basaltic dykes, emplaced at shallow depths, cutting the San Luis and Farallón Grande Formations. The volcanism is represented by felsic tuff beds in the marine Middle–Upper Eocene Barrancas Formation [62].

The youngest pre-cover deformations are recorded in the Turquino–Cayman Ridge and the Central Oriente Basin. The most remarkable by its dimensions is the great Sierra Maestra monocline, followed northward by the Central Oriente Synclinorium [115].

The composition of the San Luis Formation sandstones and conglomerates, outcropping northward of the Sierra Maestra Mountains, is typically volcanomictic, with some carbonate and granitoid clasts and without ophiolitic or metavolcanic clastics. Whereas, in the Cajobabo, Imías and San Antonio del Sur Valleys at the Caribbean Coast, in Guantanamo Province, the clastic rocks of the San Luis Formation, together with their typical volcanomictic debris, show relatively abundant clasts, clearly derived from nearby sources with ophiolitic and metavolcanic rocks (Figs. 5.17 and 5.18). In the easternmost basin locations, at the Cajobabo Valley, upon the well-stratified turbidites of San Luis Formation, lies a small klippen with Lower Eocene rocks

Fig. 5.18 of the Turquino–Cayman ridge volcanic arc [23, 25]. Near the mouth of Cajobabo River, a small serpentinite body occupies a frontal position in the clipper of T-CR rocks, emplaced upon Middle Eocene olistostrome and turbidites of the basal San Luis Formation. All these rocks are unconformably covered by Neogene–Quaternary beds (see Fig. 14 in [23]). The lower Paleogene volcanites are not present in the local autochthon pre-Eocene record and the thrusting probably was a late Middle Eocene event. In the author's criteria, these facts could be explained by the first horizontal movements along the Oriente fault zone of the Caribbean/North America plate boundary (see [72]). Particularly, the geological relationships at the coastal area between San Antonio del Sur and Cajobabo suggest a left lateral (sinestral) displacement of circa 25–30 km during a late Middle Eocene travel along the fault. As a consequence, a tectonic flake (perhaps a southern prolongation of the current Sierra del Convento ophiolitic massif), was caught by the Bartlett Land, displaced several kilometers eastward and finally located in front of the eastern Oriente basin margin, southward Cajobabo. These facts could explain the peculiar clastic composition of San Luis Formation in this area and its relationship with the tectonic emplacement of the Turquino–Cayman Ridge arc rocks.

5.3.4 The Eocene–Quaternary Cover

The cover (Neoauthocton, sensu [61]) embraces the large upper structural stage of the Cuban orogen. From Pinar del Rio to NW Holguín, it includes little deformed strata, accumulated after the Cuban orogeny. In eastern Cuba, south and east of the Guacanayabo–Nipe Bay lineament, the cover embraces the beds accumulated after the end of the Late Eocene magmatic activity (Figs. 6.19 and 6.20).

Fig. 5.17 Lower Eocene tuffs outcroping near the Caribbean coast at La Farola road, Cajobabo, Guantanamo.Th strata belong to a tectonic scale with T CR rocks (El Cobre Formation) and some slivers of serpentinite breccias (see Cobiella et al. [25], Iturralde- Vinent [54], and Cobiella-Reguera [23]). The scale (circa 5 sq. kilometers and perhaps 500 meters of maximum thickness) rests on the basal beds of the Central Oriente Intermontanious Basin

As we saw, the Cuban orogeny not concluded simultaneously throughout Cuba. There is a strong evidence of the decisive role played by several narrow strips arranged transversely to the general structural trends generated by the Cuban orogeny. These structures have a linear character (lineaments) and their development is closely related with the nature and age of the tectonic events. Four main lineaments (and several minor) are identified: (a) Yabre lineament; (b) La Trocha lineament (or fault zone); (c) Camagüey lineament; and (d) Guacanayabo–Nipe Bay lineament

Fig. 5.18 Olistostrome of the basal beds of San Luis Formation at Cajobabo. The deposit is a pile of unsorted blocks, the biggest attaining several meters.The most abundant clast lithologiesare lapillitic tuffs and agglomerates with some porfiritic andesites.Obviously they were torn from a near T-CR source rocks. Additionally, some greenschists clasts (from the Upper Cretaceous volcanic arc) and gabbro-pegmatites (from the NOB) are present.

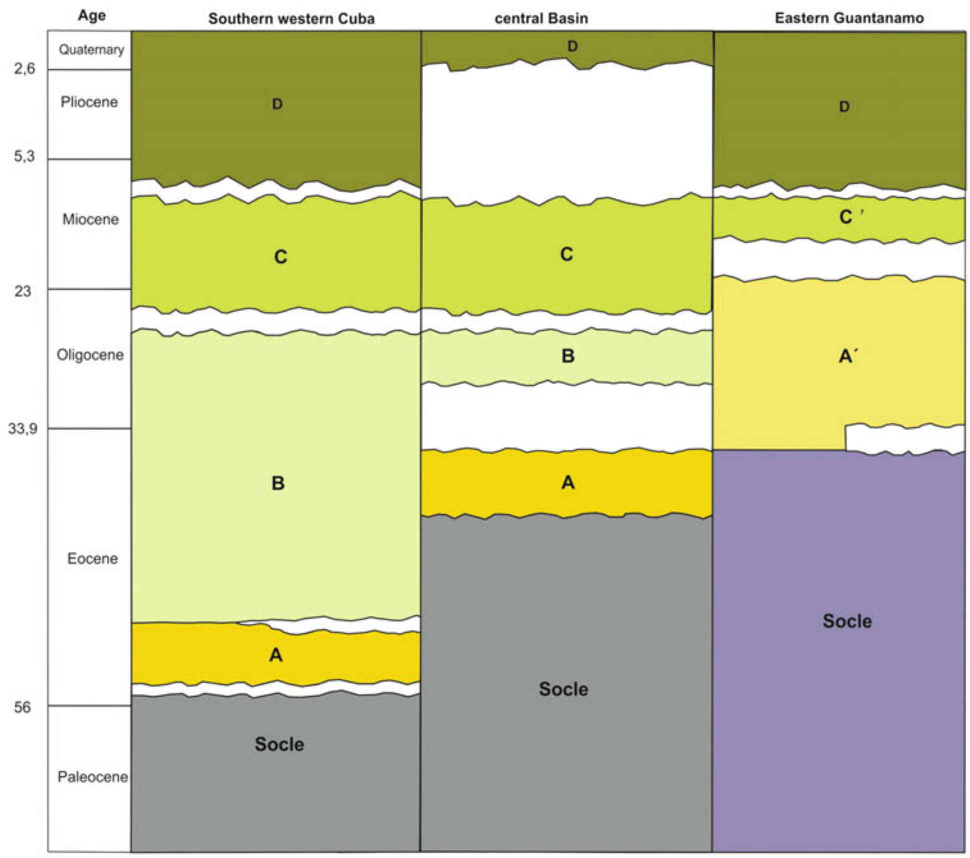

Fig. 5.19 Stratigraphic distribution of the cover sub-stages in different localities. Whereas in western Cuba the oldest cover beds are almost of basal Lower Eocene age, in central Cuba the cover begins with Middle Eocene strata and in easternmost Cuba the lowermost cover rocks settled in the latest Late Eocene. In the figure, the different nature of the socle between eastern and central-western Cuba is emphasized

(Fig. 5.1). As previously noted, the orogenic deformations are genetically linked with the arrival to the foreland basin of remarkable volumes of chaotic terrigenous deposits. Westward of the Yabre lineament these arrivals occur from Lower Paleocene to Lower Eocene. Between Yabre and La Trocha lineaments, the great terrigenous arrival developed between the Paleocene and the beginning of the Middle Eocene. Between La Trocha and Guacanayabo–Nipe Bay lineament, the orogenic events span from Middle Eocene to late Middle Eocene or early Late Eocene. Therefore, the cover bottom is markedly diachronic (from Lower to basal Upper Eocene) and the cover presents beds with ages ranging from Lower Eocene to Quaternary. Eastward of the Guacanayabo–Nipe bay lineament, instead a socle with an alpine tectonic style in its lower Paleogene rocks, a relatively little deformed and basically in situ volcanic arc (the Turquino–Cayman Ridge arc) and the Central Oriente Eocene intramontane basin beds are present. Here the cover embraces rocks from the Uppermost Eocene to the Quaternary (Figs. 5.19, 5.20).

Several major blocks with contrasting movements can be recognized related to the cover tectonics [54]. According to Cobiella (27b, modified), the following main subsiding regional blocks are present in the Eocene–Quaternary history of the cover: (1) Nipe–Baracoa Basin, (2) San Luis–Guantánamo Basin, (3) Cauto–Guacanayabo Basin; (4) Central Basin; (5) Southwestern Basin; and (6) Northcentral Basin.

Fig. 5.20 Unconformity between cover sub-stages C and D at Vía Blanca highway, La Habana. D: sub-stage D, represented by the cross-bedded Pleistocene Guanabo Formation, C: sub-stage C, represented by the shallow water, strongly weathered Lower–Middle Miocene Güines Formation

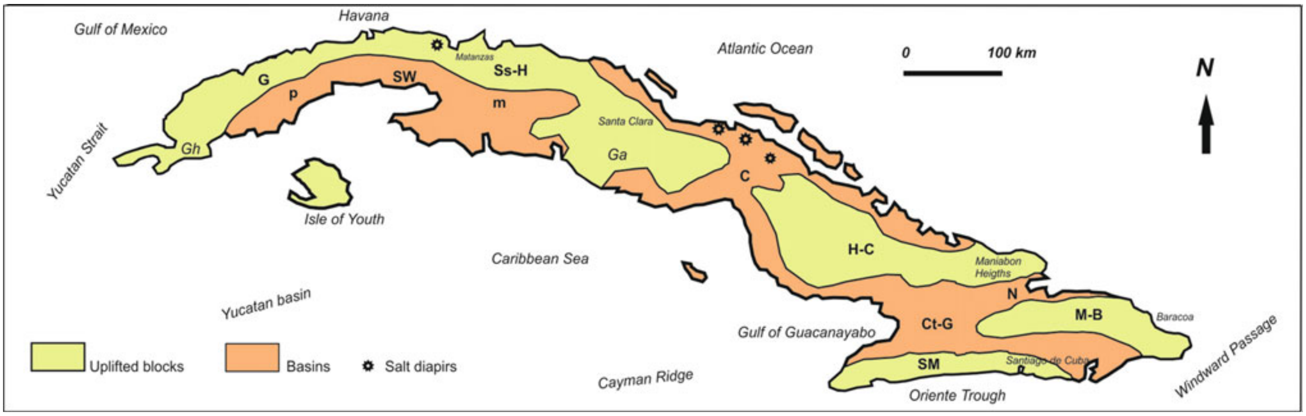

Fig. 5.21 Distribution of uplifted areas and basins in the cover from Eocene to Quaternary. Included are the localities with salt diapirs in Cuba

The coeval regional structures with a dominant rising trend are from east to west: (7) Babiney–Maisí block; (8) the Sierra Maestra Mountains; (9) Holguín–Ciego de Ávila Block; (10) Sancti Spíritus–La Habana Block; (11) Guaniguanico–Guanahacabibes Block; and (12) Isla de la Juventud Block (Fig. 5.21).

The cover outcrops in more than 50% of the Cuban territory. Using different sources, we studied the cover sediment thickness in 40 wells. Its average thickness was about 760 m, but records of 2000–3740 m are known [112]. In western and central-eastern Cuba, we can distinguish four sub-stages, arranged in the following order from bottom to top: A, B, C, and D. Their ages range from Lower Eocene to Quaternary (somewhat similar ideas on the Paleogene tectonic development, but with a different approach, are contained in Refs. [93, 106]. Meanwhile, the proximity of SE Cuba (eastward from Guacanayabo–Nipe Bay lineament) to the Caribbean/North America plate boundary makes its geological development tightly related to the history of the Cayman trough and, therefore, with particular features. In SE Cuba, three sub-stages are distinguished in our research: A', C', and D' (Fig. 5.19).

5.4 Some Comments on Certain Regional Structures

5.4.1 The Oriente Fault Zone

The deep basin that forms the easternmost Cayman Trough is called the Oriente Trough. The first ideas on the geology of the Cayman Trough developed in the 30s of the twentieth century and belongs to Stephen Taber [125] supported on general observations about the geomorphology and geology of the Sierra Maestra Mountains and preliminary information on the bottom topography. In the middle 60s, Bowin [6] presents a first geophysical model of the Cayman Trough showing the oceanic crust nature of its bottom. The picture was later enriched by Perfit and Heezen [90] with drag samples from its walls. At that time, the information on the great linear depression begin to be integrated in the first plate tectonics models related to the Middle American area, when it becomes evident the location of great strike-slip faults along its margins ([11], Cobiella-Reguera et al. [27]). A crucial finding was the location of a little N–S trending, well-defined oceanic crust formation center at the deepest part of the trench, southward of the Cayman Islands. In Cuba, some interesting results attained a group of Cuban geomorphologists working in the Sierra Maestra [48].c

An outstanding contribution to the knowledge of the Cayman Trough geology is the paper by Calais and de Lepinay [10], a seismic research on the structures of the Oriente Fault Zone (OFZ) along the northern Columbus Strait (Fig. 5.22). This study revealed several unknown features on the internal structure of the Oriente Trough. The data collected show that the OFZ is not a single dislocation, but embraces several major fractures, with a general E-NE trend, connected through several minor dislocations. The OFZ is a major sinestral fault zone. As it occurs in all the great strike-slip faults, in some sectors, compressive plicative folds and nappes develop, whereas in others normal faults and grabens are present. The most remarkable structure found is the Santiago Deformed Belt (SDB), a narrow and long compressional belt, extending from 75° to 76° 30′ W, almost in front of the Cordillera de la Gran Piedra Highlands. Some small sedimentary basins are located in the Caribbean Sea bottom, west (Chivirico Basin), and east (Imías Basin) of the SDB. Onshore, the Santiago de Cuba, the Baconao Lake Basin, and the coastal strip between Guantánamo Bay mouth and Cajobabo are recently uplifted marine basins. In these locations, sets of prograding Neogene and Quaternary beds (Fig. 5.23), several ten or a

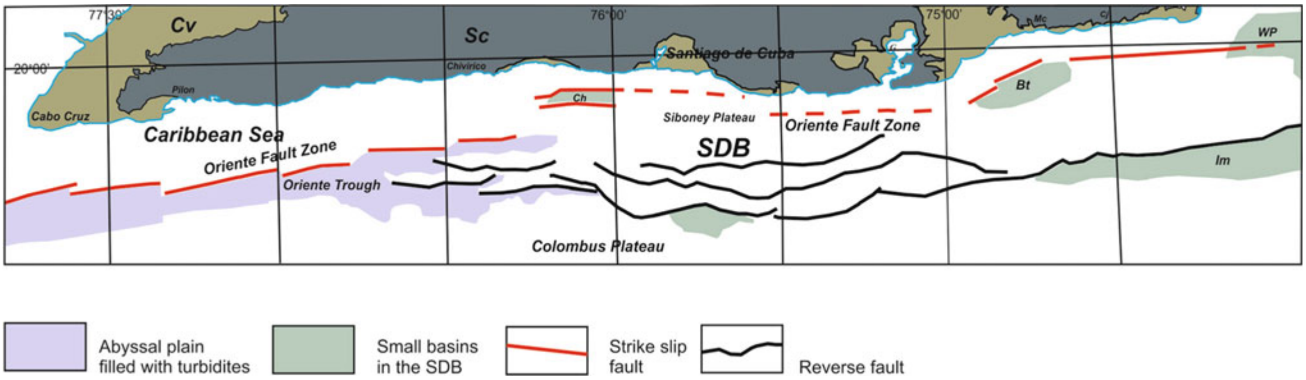

Fig. 5.22 Main structures in the Columbus strait (located between SE Cuba and Jamaica). The geologic setting is explained in the text

Fig. 5.23 Southward prograding Neogene–Quaternary beds (toward the Caribbean Coast) at Macambo, Imías, Guantánamo Province. The study of the bedding reveals at least two sets: magenta and blue lines in the photo. A third (green) set is poorly defined

hundred meters thick, southward tilted toward the shore of the Columbus Strait show that these great geomorphic structures developed at least from the Neogene. Along long tracks of the eastern Cuba's southern coast, extraordinary marine terraces, with cliffs ten meters high, cut the progradational beds.

A narrow abyssal plain, probably filled with turbidites, develops at the deepest portion on the Oriente Trough, almost at 7 km deep [49], and only several kilometers southward of Pico Turquino, the highest summit in Sierra Maestra (circa 2 km high), immediately westward of the SDB. Interesting data and ideas on the tectonic development of the eastern Oriente Trough report [10]. Supported on their interpretation of seismic profiles from the Imías and other small basins located near the Windward Passage, a five-stage tectono-sedimentary succession (correlated with nearby territories, including the Cuban SE tip) was proposed [10]. However, the correlation with neighboring inland Cuba is weak and demands further researches.

5.4.2 A Joint Study of the Regional Neotectonics and Well Data in Western Cuba

The PFZ is a polemic structure, with a general WSW-ENE trend and excellent geologic and geomorphologic contrasts with Los Palacios Basin from El Sábalo, at SW Pinar del Río Coast, to Cayajabos, in Artemisa Province (Fig. 5.2). Eastward of the last locality, the geomorphic evidence is less clear. However, NAP outcrops, with typical lithologies from the SR-APN-E units, appear in the Martin Mesa outlier, located E-NE of Cayajabos Town, and only a few kilometers from the western surroundings of La Habana (Fig. 5.2). In the eastward continuation of the fault trace, wells with NAP are present to the north, in the Mayabeque and Matanzas oil fields, whereas ophiolites and the KVAT outcrop to the south (Pérez Othón and Yarmoliuk 1984) in antiform structures from the Vegas Basin.

A remarkable topographic jump exists along the western PFZ. In the northern block, the Guaniguanico Highlands summit near the FZ attain circa 600 m in the Sierra del Rosario and more than 400 m in Alturas de Pizarras del Sur, whereas the rolling lowland surface at the Los Palacios Basin descends from heights circa 100 m at Guaniguanico foothills, to sea level at the Caribbean shore. Saura et al. [117] studied the northeastern Los Palacios Basin near Candelaria, using the results of recent seismic profiles and information from two old wells. They consider the FZ as two south-dipping fractures (approximately 50°), welded in one at approximately 1.5 km depth. These authors collected kinematic indicators in different places where fault planes outcrop. The oldest evidences record strike-slip motion along the fault. A second deformation stage consists mainly of SE-plunging slickensides and striate that suggest a dip-slip movement. Structurally, the western half of Los Palacios Basin is a great southeast-gently dipping monocline, with some minor unconformities.

In the most complete study on the PFZ, Gordon et al. [43] discriminate five phases in its history. In their opinion, the first is related to the early Paleogene thrusting event during the Cuban Orogeny. The second (compressive) sinestral phase occurs shortly after the settling of Capdevila Formation (Early Eocene), and prior to the Middle Eocene. The third phase is also a compressive ENE–WSW deformation, overprinting older faults with strike-slip features. Probably, after a 30 my quiescence, the fourth phase developed. It is a N–S extensional post early Miocene event. The fifth and last phases, slightly younger than the normal faults, are represented by a wrench faulting episode, related to ESE–WNW compression.

The Los Palacios Basin is the westernmost depression of the Southwestern Cuban Basin (SWB), a group of related Cenozoic Basins located from the southern half of Pinar del Rio and Artemisa Provinces (Los Palacios Basin) that eastward continues in Mayabeque Province (the Vegas and Broa depressions) and continues in Matanzas (Mercedes Basin) ending in the Cienfuegos Basin Fig. 5.21. The Los Palacios Basin contains a relatively thick siliciclastic-carbonate fill. A northern source, located in the Guaniguanico cordillera, is clearly evident in the clastic composition of its younger sediments. However, an older southern source perhaps was present in its earliest development, during the Early Eocene, because siliciclastic grains derived from the erosion of metamorphic and volcanic rocks (the dominant pre-Cenozoic lithologies in the Isla de la Juventud) are abundant in the Lower Eocene Capdevila Formation, but clasts from the NAP are almost absent in the strata older than the Middle Eocene (older than Loma Candela Formation). The thickness of the Eocene–Quaternary fill fluctuates between several meters and more than 2400 m [112].

An integrated study of the main western Cuba neotectonic features Fig. (5.21) and the well data in Perez Othón and Yarmoliuk [112] reveals some basic facts and trends to understand the regional structures. In those wells located in the interior of the southwestern basin, the Mesozoic basement rests below a thick Eocene–Quaternary cover. In Vegas 1, Mercedes 1, and Ariguanabo 2 wells, ophiolitic rocks rest on their bottoms (Fig. 4 in [18]). Above, with tectonic contact, lie KVAT beds, including its Campanian–Maastrichtian cover, and some lower Paleogene piggyback basins. Guanal 1 hole, near La Coloma, Pinar del Rio Province, is a shallow well where the KVAT rocks unconformably rest below the Cenozoic cover.

Northward of the SW basin extends the Sancti Spiritus-La Habana Block (SS-H, Fig. 5.21), an uplifted structure with a thin cover and wide outcrops of different Mesozoic units. In northern Matanzas Province, several antiforms (Fig. 5.24, [95]) show cores that resemble tectonic mosaics, with outcrops from the NAP (Placetas TSU), the NOB, and the KVAT. Westward, at northern Mayabeque and Matanzas, is located the petroleum geologist's "Belt of Heavy Oils." In many wells of the belt, below the cover, nappes of Placetas and Camajuaní TSUs, with tectonic wedges of the foreland basin, are present.

In the Guaniguanico cordillera Block, denudation attains its maximum depth in western Cuba and the deeply covered structures in the Southwestern basin and Sancti Spiritus -Habana Block widely outcrops. Therefore, in the Cordillera, the structural relationships between the distinct socle units are much more visible. In the eastern Sierra del Rosario Highlands, the tectonic units of the Mesozoic basement and the Paleogene fold and thrust belt are essentially located in the following structural positions (from uppermost to lowermost): (a) Paleogene piggyback Basins, (b) Cretaceous volcanic arc terrane (including Campanian–Maastrichtian sedimentary cover), (c) Northern Ophiolite Belt, (d) North American paleomargin, (Pan de Guajaibón TSU, Placetas TSU), and (e) Paleogene Foreland Basin.

It is a crucial fact that the Upper Jurassic–Lower Eocene section in the Belt of Heavy Oils is similar to the coeval beds in SR-APN-E and its overlying foreland basin.

Finally, in central Cordillera de Guaniguanico Mountains, the Sierra de los Órganos karstic landscapes are developed on the mainly carbonate Upper Jurassic–Cretaceous sections where they outcrop the core of the nappe structures of western Cuba (Fig. 5.4) with some foreland wedges (Fig. 5.5).

From the preceding review, we can suggest that the same regional tectonic units could be present along all western Cuba, from Pinar del Río to Matanzas Provinces, a very attractive fact for onshore hydrocarbon search.

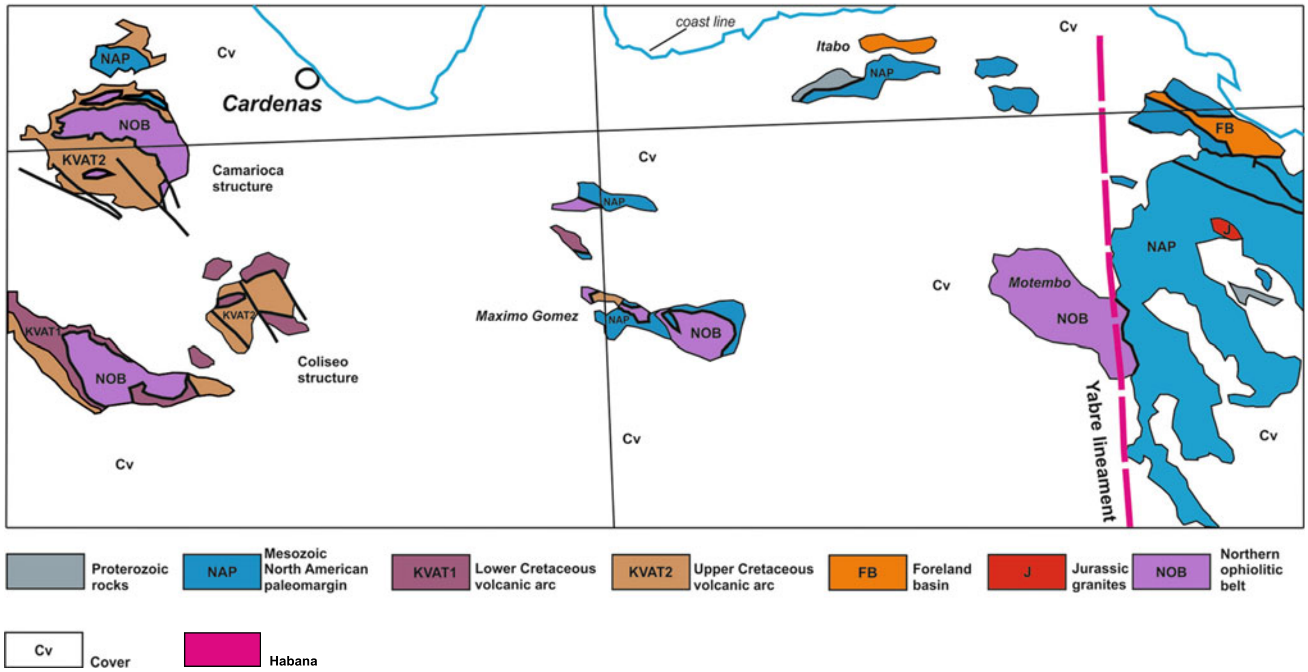

Fig. 5.24 Simplified tectonic map of NE Matanzas and NW Villa Clara Province. The structural setting is explained in the text. Very important are the two small outcrops of Precambrian metamorphic rocks near Itabo (Matanzas) and Motembo (Villa Clara)

5.5 Conclusions

In this chapter, the author presents his approach to several items on the regional tectonics of Cuba and its surroundings. Nobody can deny that the Cuban territory presents a complex geology, additionally increased by its tropical weathering and extensive territories with a discrete relief and relative few outcrops. The proposed tectonic scheme departs essentially from the last geologic (Pushcharovsky ed. [110]) and tectonic (Pushcharovsky ed. [110]) maps of Cuba, plus the main achievements attained in the regional geology studies in the last 30 years. However, we must also return to the study of valuable old data that we consider still not enough exploited, as several cases in the preceding pages show. It is evident that in the next years, the resources for the geological research in Cuba still will be limited. An important alternative way to improve and increase our knowledge on the tectonics of Cuba with minimum resources is extracting the maximum from the abundant old information and confront it with the new one, with a dialectic approach, under the light of plate tectonics, sequential stratigraphy, sedimentary basin analysis, and other paradigms developed in the last decades.

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