STRUCTURE AND TECTONICS OF THE YUCATAN BASIN, CARIBBEAN SEA, AS DETERMINED FROM SEISMIC REFLECTION STUDIES

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Abstract. The Yucatan Basin preserves a record of the Late Cretaceous to Paleogene Caribbean-North American convergent history that is largely unaffected by Neogene strike-slip tectonics of the current plate boundary. An examination of seismic basement within the Yucatan Basin, based upon available seismic reflection data including extensive multichannel data, shows that the basement comprises nine domains distinguished on the basis of internal reflection character and surface topography. These domains encompass three distinct crustal types or blocks. The first underlies the western flank of the basin and represents the offshore continuation of the adjacent Yucatan platform. The second includes the topographically heterogeneous domains of the eastern two-thirds of the basin, and is dominated by a subsided volcanic rise or arc (Cayman rise) resting upon probable oceanic crust of pre-Tertiary age. The eastern edge of the rise and adjacent basins dips northeast beneath the Cuban margin along a sediment filled trench. The third type of crust occupies a rectangular deep within the western third of the basin. Available evidence indicates that this crust is oceanic in character, and represents a large, mature pull-apart basin set within a wide paleo-transform zone between the western platform and eastern oceanic basin. This zone defines the northwestern portion of the Caribbean-North American convergent plate boundary. Paleocene to Middle Eocene transform motion was left-lateral along north-south to NNW-SSE trends, with a displacement of about 350 km. A long Middle Eocene transcurrent fault of about 50 km left-lateral displacement cuts the basin diagonally from SW to NE and continues onland in Cuba as La Trocha fault. This reconstruction is consistent with known Eocene regional tectonics, but the timing of regional events raises questions about present interpretations of plate geometry in the northwestern Caribbean.

INTRODUCTION

The Yucatan Basin occupies a significant position with respect to northern Caribbean plate boundaries because it lies adjacent to the Late Cretaceous to Middle Eocene convergent boundary transecting Cuba, Hispaniola and Puerto Rico, but outside the younger, present-day transform plate boundary extending from Honduras to Puerto Rico (Figure 1). Because this younger boundary has dissected and overprinted much of the older convergent boundary, the basin should contain a record of the convergent history of the Caribbean plate that is unaffected by later events, and so should provide insight as to the nature and timing of the transition from convergent to transform plate motion.

Unfortunately, the geology of the basin has been sparsely sampled and the record of geological and tectonic events is unclear, especially as to the composition and age of the crust. Seismic refraction profiles and regional gravity interpretations suggest that crust beneath the deep north-central and western parts of the basin is oceanic, but that the crust thickens southward to more than 20 km beneath the Cayman ridge [Ewing et al., 1960; Dillon et al., 1972; Dillon and Vedder, 1973; Bowin, 1968; 1976]. Rocks dredged from the southern wall of the Cayman ridge include volcanics and metavolcanics as well as granodiorites with K/Ar cooling ages of 59 to 69 Ma (Maastrichtian to Paleocene), which suggests that this thicker crust represents a buried Late Cretaceous island arc resting on Late Cretaceous or older crust [Perfit and Heezen, 1978]. Inferred ocean crust beneath the deep western part of the basin appears younger, however, Late Paleocene to Middle
Eocene on the basis of heat flow [Epp et al., 1970; Erickson et al., 1972] and depth to basement measurements [Rosencrantz et al., 1989]. In contrast, samples dredged and drilled along the western flank of the basin include metasediments lithologically similar to Paleozoic rocks found at depth across the Yucatan platform [Dillon et al., 1972; Dillon and Vedder, 1973; Deal, 1983; R. P. Rao, personal communication, 1988], with metamorphic textures similar to those identified as Late Cretaceous in age in central and western Cuba [Baie, 1970; Pyle et al., 1973; Vedder et al., 1973; Hatten et al., 1988]. Seismic reflection surveys of the western flank and adjacent deep basin by Dillon and Vedder [1973] and Uchupi [1973] lead both to interpret this margin as representing an old passive rift margin.
This paper examines available seismic reflection data from the Yucatan Basin to determine basin tectonics as revealed by the distribution of basement seismic character and structure. The approach used here differs from previous work [e.g., Dillon et al., 1972; Dillon and Vedder, 1973; Uchupi, 1973; Tinkle, 1981] in that it examines the whole of the basin rather than just its western part, and incorporates and correlates all available seismic data, including the large volume of unpublished University of Texas Institute for Geophysics (UTIG) multichannel seismic (MCS) data. This larger set of information shows a basin underlain by crust of complicated internal structure, composed of oceanic crust of two different origins plus continental crusts, distributed across two plates.

SEISMIC REFLECTION DATA

Seismic reflection profiles used in this synthesis include both single and multichannel data. The multichannel seismic (MCS) data were acquired by UTIG during five separate acquisition programs between 1975 and 1980. These data were collected using large-volume, low-pressure airguns or explosive sources, shot to 24 or 48 channel streamers of 2 to 4.5 km length, and were digitally processed at UTIG with standard techniques. These profiles are previously unpublished, except for one presented by Tinkle [1981] and another included in Rosencrantz et al. [1989]. The single channel seismic (SCS) data were acquired between 1961 and 1973 on thirteen separate cruises by a number of institutions, with data collected using airgun and sparker sources. The majority of these also remain unpublished, except for several presented by Dillon et al. [1972], Vedder [1972], Uchupi [1973] and Dillon and Vedder [1973]. Table 1 lists data source and type. Figure 2 shows profile locations.

Although the amount of available seismic reflection material appears extensive, these data are in fact limited in several respects. The overall coverage of the basin is sparse in view of the morphological and structural complexity of the region. Matching reflector sequences between profiles of different vintages is often difficult owing to differences of scale and resolution. Older profiles are commonly not well navigated. Variations of source signature produce significant differences in reflection character, and differences in source strength result in varying degrees of bottom penetration. Because the multichannel seismic lines show the deepest penetration and have the most consistent source signatures, descriptions are based primarily on the the MCS lines, supplemented by single channel data.

BASEMENT STRUCTURE

Basement is defined as the seismic unit below the deepest continuous seismic horizon, defined as the basement horizon. This horizon is almost always marked by a distinct, high amplitude reflection or group of reflections. It occupies the same position relative to overlying sediments as the Late Cretaceous B horizon in the Venezuelan Basin [Edgar et al.,

<table>
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<td>USNS Wilkes-W193008</td>
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Projects: YB, Yucatan Basin survey; GT2, Gulf of Mexico Tectonics-Phase 2; CT1, Caribbean Tectonics-Phase 1; CT2, Caribbean Tectonics-Phase 2; CAR, Caribbean phase of IPOD site surveying. Agencies: UTIG, University of Texas Institute for Geophysics; LDGO, Lamont-Doherty Geological Observatory; WHOI, Woods Hole Oceanographic Institute; USCGS, United States Coast and Geodetic Survey; URI, University of Rhode Island; USGS, United States Geological Survey; TAMU, Texas A&M University; NAVOCEANO, (United States) Naval Oceanographic Office. Published sources: *Vedder [1972]; Dillon and Vedder [1973]; *Uchupi [1973]; *Tinkle [1981].
Fig. 2. Index map showing the location of seismic profiles, plus the positions of bottom sampling stations and wells discussed in the text. Data are derived from the following sources: seismic reflection lines, Dillon and Vedder [1973], Uchupi [1973], Tinkle [1981]; seismic refraction profiles, Ewing et al. [1960]; heat flow stations, Epp et al. [1970], Erickson et al. [1972]; piston core locations, T. Holcombe [personal communication, 1988]; dredge locations, [Dillon et al. [1973], Pyle et al. [1973], Perfit and Heezen [1978]; well locations, Deal [1983].

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**Yucatan Basin Index to Data**

- Multichannel seismic profiles
- Single channel seismic profiles
- Refraction profiles

**Legend:**
- [1] Basil Jones #1
- [2] Turneffe #1
- [3] Glover#1
- [4] Spanish Lookout #1
1973], but is apparently not equivalent in age or origin because the Yucatan basin horizon records events younger than those associated with the B' reflector (see below).

The basement unit shows four distinguishing characteristics: (1) large scale (> 1 km), basin-wide relief of the basement horizon, mapped in Figure 3; (2) large scale basement structure, consisting predominantly of reflector and topographic offset, interpreted as representing faults, mapped in Figure 4; (3) distinctive small scale topography and/or distributions of reflections at the basement horizon; and (4) distinctive distributions of reflections internal to basement.

The dominant characteristic of basement is its surface topography, which controls the overall morphology of the basin. Differences of small scale basement seismic structure correlate with large scale basement relief, indicating that basement relief reflects variation in crustal structure. On the basis of these differences, the basement underlying the basin can be divided into 9 crustal domains. These are outlined in Figure 5, and are described below.

Domain A: The Yucatan Borderland

The Yucatan borderland underlies the western flank of the Yucatan Basin, from Cuba to Honduras (Figure 5). Basement includes three linear topographic elements extending the length of the domain: a trough aligned along the domain axis, an outer topographic high parallel to and east of the trough, and an outer escarpment which slopes eastward from the outer ridges (see Figures 3 and 4).

The central trough, known as the Dangria trough in Belize [Rao and Ramanathan, 1988], lies between 35 and 65 km east of the Yucatan coastline. It is composed of a series of connected, elongate deeps distributed en echelon, with right-handed sense, on a NNE-SSW trend. Individual deeps range in length from 40 to 80 km, in width from 15 to 30 km, and have maximum depths of between 3.5 and 4.5 km. They commonly show asymmetrical cross sections, wherein western, east-dipping basement slopes have shallower dips than eastern, west-dipping slopes. Basin axes and eastern slopes are characterized by west vergent (down-dropped to the west) normal and reverse offsets trending subparallel to basin length (Figure 6).

The topographic high east of the central trough contains two lines of discontinuous, steep-sided, linear ridges which trend NNE-SSW. These ridges range in length from 20 to 60 km, and have an average width of about 12 km (Figures 3 and 4). North of Chinchorro Bank (about latitude 19° N) the ridges reach minimum depths of about 1 km, but south of this latitude they approach the surface and emerge at Chinchorro Bank, Turneffe Island, and Glover Reef. To the south the ridge lines are separated by about 40 km, but converge to about 20 km in the north. Individual ridges along each line show a slight, dextral en echelon placement. The eastern side of the borderland is defined by a major escarpment with an average relief of about 3.5 km. Maximum crest to base relief is over 5 km. The escarpment extends essentially unbroken from Cuba southward to latitude 18° N, where it is offset 15 km to the east. Southward past the offset it again continues unbroken along the east side of Glover Reef (Figure 3). North of the offset, the escarpment slopes to the east with an average dip of about 10°. South of the offset this slope exceeds 18°. A line extending WNW from the offset to the northern edge of Banco Chinchorro marks a boundary between shallow southern ridge tops and deeper northern ones, and may trace the line of a cross-margin fault.

Base ment beneath the central trough contains numerous internal reflections that lie subparallel to the basement horizon. These have a discontinuous hummocky appearance, and include local high angle offsets. The basement horizon consists of a distinct but discontinuous reflector of hummocky appearance describing a surface of low relief (<250 m). The unit is apparently continuous with units (and rocks) underlying the Yucatan platform to the west. To the east, reflections cannot be traced beyond the eastern edge of the central trough (Figure 6, kilometers 70 to 72). Whether this is due to basement unit truncation, or is simply an artifact of source energy scattering by the rough basement of the outer ridge, cannot be determined from the seismic data.

Domain B: Southwest Horst and Graben

The southwest horst and graben domain is located at the southwest end of the Yucatan basin, between the Yucatan borderland and the western Cayman ridge (Figure 5). It is bounded by the Yucatan borderland escarpment to the west and by the NE-SW trending, west-facing escarpment truncating the western end of the Cayman ridge to the east. Basement is pervasively broken by a series of NNE-SSW trending horsts and grabens. The geometry of the basement surface suggests that blocks have tilted and rotated, although the blocks are internally featureless, and their tops commonly indistinct where buried beneath thick sediments (Figure 7). Fault spacing perpendicular to trend averages about 10 km, and relief of fault scarps ranges from a few hundred meters to over 2 km. The average depth of basement is about 5 km.

Domain C: Western Deep Basin

The western deep basin domain covers a rectangular area, 140 to 170 km wide and 330 km long, oriented NNE-SSW, adjacent to and east of the Yucatan borderland (Figure 5). The domain is bordered on all sides by basement scars or offsets (Figure 4). Basement is relatively flat, with depths ranging from 5 to 7 km, with an average of about 6 km (Figure 3). The basement horizon consists of nested, high amplitude diffraction hyperbolae describing a surface of moderate (200 to 500 m) relief. The basement complex contains no persistent internal reflectors, except at depth on profiles shot with high energy sources [Rosencrantz et al., 1989] (Figure 8).

The western deep is separated from the Cayman rise (see below) to the east by several NNE-SSW trending basement scarps and lineaments, interpreted to represent fault lines (Figure 8, kilometers 180 to 200). Both the northern and southern boundaries are characterized by WNW-ESE trending basement scarps which may include faults (Figure 9, kilometers 20 to 30). The western edge of the domain lies along the base of the Yucatan borderland escarpment. Adjacent to the escarpment between latitudes 19° and 20° N, a small wedge-shaped area contains a NE-SW trending trough of 7 km depth and an adjacent parallel ridge of about 4.5 km depth (Figure 3). The basement horizon within the area is
Fig. 3. Depths to the basement horizon. Depths, in kilometers, are calculated as sums of water depths plus sediment thicknesses as calculated from multichannel seismic profiles, and include the effects of present sediment loading.
characterized by a discontinuous reflector of moderate relief (250-750 m). Internal reflectors are discontinuous, hummocky, and dip relative to, and are truncated by, the basement horizon.

**Domain D: Northwestern Rise**

The northwestern rise lies to the north of the western deep basin, south of Cuba and west of the Isle of Pines (Figure 5). Basement rises northward across a series of topographic steps to a minimum depth of 4 km, then drops across a north-facing scarp just south of the Cuban margin to a depth of over 5 km (Figure 3). Basement relief is probably generated by faulting of unknown strike. The basement complex contains no distinct internal reflections. The basement horizon is defined by a strong reflection, smooth along the lower, southern part of the rise (see Figure 9, kilometers 30 to 45, and Figure 10, kilometers 15 to 60), but characterized by high amplitude diffraction hyperbola across the higher, northern parts of the domain (Figure 9).

**Domain E: Central Seamounts**

This small domain is located central to the Yucatan Basin, between the western deep basin and eastern basin (see below) (Figure 5). It contains isolated, irregular basement highs and deeps of more than 2 km maximum relief (Figure 3). Basement within the area is internally featureless, but has an irregular surface characterized by common nested hyperbolas, as shown in Figure 10 (kilometers 60 to 105). Basement topographic offsets suggest that the domain is cut by several NE-SW trending faults (Figure 4), but the basement complex shows no obvious structural break with deeper crust to the northeast and southwest.

**Domain F: Eastern Basin**

The eastern basin domain occupies the northeastern corner of the Yucatan Basin, between the Cayman rise (see below) and steep escarpments of the Cuban margin (Figure 6). Basement depths range from 5 to slightly over 6 km, but reach 6.5 to 7 km along a north-south trending linear deep located south of the Isle of Pines (see Figure 3). Basement west of this lineament is flat with a slight southward slope, whereas basement to the east shows some relief, increasing eastward (Figure 4). The basement horizon consists of a strong discontinuous reflector with low to moderate relief, with minor fault disruptions and diffraction hyperbola (see Figure 11). The basement complex shows uncommon indistinct and discontinuous internal reflectors.

**Domain G: Cayman Rise**

The Cayman rise domain occupies the triangular area between the deeps of the western and northern Yucatan Basin.
and the Cayman ridge (Figure 5). The domain is characterized by a broad topographic rise across the southern part of the basin. The linear crest of the rise lies at depths of greater than 2.6 to 2.8 km, and contains several individual peaks or seamounts which rise to less than 2 km. A carbonate pinnacle known as Pickle Bank caps the easternmost of these peaks (Figure 3). To the west the rise takes on the character of an irregular plateau lying at a mean depth of about 3.5 km (Figure 10).

The basement horizon is characterized by a strong discontinuous reflector of hummocky appearance, with uncommon, subdued diffraction hyperbola, except along the crest of the rise, where the basement reflection becomes diffuse and merges with overlying sediments (Figure 12, kilometers 58 to 88). The surface shows moderate small scale relief of apparent constructional origin. Uncommon reflectors internal to the basement unit range in appearance from chaotic to discontinuous parallel. Basement offsets are uncommon and do not directly disrupt overlying sediments.

Basement south of the rise crest, between the crest and the Cayman ridge, is cut by a series of ENE-WSW trending horsts and grabens. These extend from longitude 79°W west to 83°W in a zone about 50 km wide (Figure 4). Individual grabens range in width from 10 to 20 km, and have a maximum relief of up to 2 km (Figures 10 and 12). Basement faults within the zone of grabens locally disrupt and displace the deepest of the seismic facies units. At longitude 82.5°W, this zone intersects a linear, fault bounded topographic deep which cuts across the rise with a north-south trend at depths exceeding 5 km (Figure 3). The structure is similar in size and orientation to the one cutting the eastern basin to the north.

The Cayman rise is separated from domains to the west and north by a series of northwest facing slopes and escarpments that define a topographic lineament extending from the western end of the Cayman ridge northeast to central Cuba (Figure 4). This lineament is most extreme at the western end of the rise (and western end of the adjacent Cayman ridge) where it consists of a single escarpment up to 2.5 km high. Adjacent to the western deep basin the lineament is defined by a series of scarps and linear valleys along the base of a rugged NW dipping slope. South of the central seamount domain, basement along and to the south of the lineament shows evidence of block faulting, with overlying sediments both offset and deformed (Figure 11, kilometers 122 to 132). Further northeastward, the lineament follows a ENE-WSW trending, north facing scarp separating the rise from the eastern basin (Figure 11, kilometer 95). Along the northeastern part of the rise, however, the lineament is expressed only as a zone of anomalously rough basement (Figure 12, kilome-
Domain H: Cayman Ridge

The Cayman ridge, located between the Cayman rise and the Cayman trough (Figure 5), is a ENE-WSW trending crest defined by the 2000 m basement (and bathymetric) contour (Figure 3). The geometry and reflection character of the basement surface suggests that basement blocks are faulted and tilted, although basement underlying the ridge shows either chaotic internal reflectors or no internal reflectors. Individual blocks defining the crest of the ridge lie parallel to the ridge trend, except at the eastern end where individual blocks show a slight dextral en echelon distribution relative to the ridge trend (Figure 4). The western extension of the Sierra Maestra mountain range in southern Cuba is not topographically continuous with the ridge but lies to the south of the eastern ridge crest (Figure 4). To the west the ridge is truncated by the 2.5 km high, NE-SW trending scarp that defines the eastern boundary of the southwestern horst and graben domain.

Domain I: Camagüey Trench

The eastern edge of the Cayman rise intersects and dips beneath the southwestern Cuban margin along a NE dipping thrust zone (Figure 13). The basement horizon describes a trench, designated the Camagüey trench, which extends from latitude 20° N in a curve south and east toward the Cauto Depression (Figures 3, 4). Basement depths within the trench reach a maximum of about 6.5 km along the axis. The deepest of the sedimentary deposits filling the trench display west-vergent thrusts and folds (Figure 13).

DISCUSSION AND INTERPRETATION

Distribution, Composition, and Age of Basement

The reflection character of the basement unit, including the relief of the basement horizon, the geometry of faults cutting the basement unit, indicate that the Yucatan Basin includes three distinct and separate blocks of crust. The first block includes the Yucatan borderland domain, plus the southwestern horst and graben domain. The second includes the
Fig. 7. Multichannel seismic reflection profile (UTIG profile CT1-35) across the southwest horst and graben domain. Diagram elements are the same as in Figure 6. See the inset map and Figure 5 for profile location.
The Yucatan borderland block. Seismic profiles across the Yucatan margin (Figure 6) indicate that the stratigraphy of the Yucatan platform [Bateson, 1972; Bateson and Hall, 1977; Lopez-Ramos, 1975; Weidie et al., 1979; Viniegra-O., 1981] extends offshore beneath the borderland. The Basil Jones #1 well, located on the Belize coastline and on the eastern edge of the Corozal Basin (see Figure 2 for location), includes about 100 m of Tertiary limestones, 1900 meters of Mesozoic shallow water carbonates and evaporites, a thin Jurassic red bed, and about 100 m of Paleozoic shale resting on schist [Lopez-Ramos, 1975]. Rao and Ramanathan [1988] show that the offshore stratigraphic section measured at the Turneffe #1 well section correlates with well sections in the Corozal Basin.

The Turneffe section, located on the outer ridges of the borderland, demonstrates that the platform section extends across the central trough beneath the southern outer ridges, and the composition of basement rocks dredged and drilled along the outer ridge of the borderland show crystalline rocks lying at depth beneath the platform extend to the borderland escarpment. The Glovers Reef #1 well penetrates Paleozoic shale similar to that of the Maya Mountains [Dillon and Vedder, 1973]. Baie [1970], Dillon et al. [1972], Dillon and Vedder [1973] and Vedder et al. [1973] all observe that altered basic extrusives, deformed metamorphosed (low grade) shale, siltstone and quartzite, metamorphosed (green-schist facies) phyllites, and foliated marbles dredged from the outer escarpment at depths between 4200 and 2700 m are equivalent to Yucatan Paleozoic rocks. Pyle et al. [1973], on the other hand, suggest that these, on the basis of their metamorphic character, correlate to the Middle Jurassic San Cayetano Formation of western Cuba.

The lack of dredged carbonate and evaporite samples probably reflects the small numbers of rocks collected, but could also mean that these lithologies either were not deposited on, or have since been eroded from, the outer margin. A schist pebble conglomerate with a Late Eocene-Early Miocene matrix dredged from the northern escarpment [Vedder et al., 1973] hints that the northern outer ridges may
have included crystalline basement exposed during the Eocene. The age of the basement horizon across the borderland is not known for certain, but is likely to be Eocene. The synclinal cross section of the layered basement and onlapping of overlying sediments (Figure 6) implies that the horizon marks a tectonic event. The distinct difference in reflection characters of sediments above and the basement unit below the horizon imply a distinct change in lithology across the horizon. The Late Eocene and younger schist pebble conglomerate noted above is consistent with an Eocene or older tectonic age for the horizon. The Turneffe #1 and Spanish Lookout #1 wells penetrate Middle Eocene and younger reef carbonates, lagoonal carbonate muds and terrigenous sediments (Belize Formation), which rest unconformably on Paleogene-Late Cretaceous deep water clastics (Toledo Formation) in the Turneffe well and massive biomicrites (Campur Formation) in the Spanish Lookout well [Rao and Ramanathan, 1988; R. P. Rao, personal communication, 1988]. The hiatus between the Belize formation and underlying units becomes more pronounced southward, extending into the Miocene. This would suggest that lithologies above and below the basement horizon respectively represent the Belize and Toledo-Campur formations. However, Rao and Ramanathan [1988] also show (in cross section) that both the Belize and underlying Campur Formations thin or pinch out to the west at the coastline along north-south faults which define the western edge of the Dangria trough. As the Campur formation also rests with distinct unconformity upon Late Cretaceous dolomites and evaporites of the Coban formation, the basement horizon might also be reasonably interpreted as a Late Cretaceous surface between the Belize-Campur and Coban units.

East-west free air gravity profiles across the southwest horst and graben domain show that underlying crust thins eastward, from about 20 km beneath Glovers Reef Bank to about 8 km beneath the western end of the Cayman trough [Dillon and Vedder, 1973]. The composition of the crust is not known directly, but the thinning and block faulting suggest that it may be stretched continental crust.

The eastern block. Crust underlying the area east of the western deep basin, including the eastern basin, central sea-
mounts, Cayman rise, Cayman ridge and Camagüey trench domains, is likely contiguous and of common origin. No obvious structural break is observed between the central seamounts and the eastern basin, nor between the Cayman rise and Camagüey trench. The Bouguer gravity field [Bowin, 1976] and free air gravity profile models [Bowin, 1968] both indicate that crust beneath the rise is laterally continuous with that beneath the eastern deep basin. The Cayman rise intersects and topographically merges with the Cayman ridge west of longitude 83°W. The reflective and small scale topographic characters of the basement horizon within the eastern basin are similar to those of the Cayman rise, and the basement complexes of both domains show uncommon internal seismic layering.

The irregular topography of basement, the presence of seamounts along a linear topographic crest, and likely presence of volcanoclastic deposits on the rise crest [Perfit and Heezen, 1978] all imply that the Cayman rise has a volcanic origin. Seismic refraction profiles show that the crustal thickness of the rise is at least 14 km [Ewing et al., 1960], and gravity modeling suggests that it exceeds 18 km, thinning to the north [Bowin, 1968]. The basement horizon corresponds to the top of a 2.6 km thick 4.8 km/s seismic refraction interval [Ewing, et al., 1960] (Figure 12). Perfit and Heezen [1978] argue that this seismic unit represents volcanics, clastics and metasediments, plus carbonates, of Paleocene to Eocene age, as sampled at the western end of the south wall of the Cayman ridge. They further argue that the underlying 6.5 km/s velocity layer consists of Cretaceous amphibolites and Late Cretaceous to Paleocene plutonics, volcanics and volcanoclastics.

The Cayman ridge undoubtedly includes Cayman rise crust, uplifted in response to plate motion along the Oriente transform fault to the south. The two structures intersect, and apparently have a common lithology [Perfit and Heezen, 1978]. A single, shallow seismic refraction profile near Grand Cayman Island shows crustal velocities broadly similar to those of the rise to the north [Ewing et al., 1960]. Seismic reflection profiles across the ridge show that it is separated from the rise by a line of ENE-WSW faults along its north side, particularly along the eastern half of the ridge. Crustal blocks within the ridge are apparently tilted (Figures 10 and 12). The Middle Eocene opening of the Cayman Trough [Rosencrantz et al., 1988] implies that the ridge had formed at least by Eocene time. The earliest record of crustal movement along the ridge is one of subsidence, however, in that the distribution of dated carbonate rocks dredged from the ridge show the western ridge subsiding by Miocene time. Oligocene and older carbonates have shallow water origins, whereas younger carbonates include both deep and shallow water varieties [Perfit and Heezen, 1978].

Crust beneath the eastern deep basin is probably oceanic, but may not be typical oceanic crust. A single refraction profile south of the Isle of Pines (Figure 2) shows an 8 km
thick crust with an oceanic velocity structure [Ewing et al., 1960]. Oceanic crust is consistent with the regional gravity signature [Bowin, 1968; 1976], but the basement does not show the rough topography and nested hyperbolas characteristic of oceanic crust, as evident within the western deep basin. The basement block faulting seen in the eastern basin is also atypical. Mean depths to basement (with the loading effects of sediments removed) are less than those of the apparently younger western deep basin, about 5100 m versus about 5300 m. This difference is also reflected in the regional free air gravity anomaly field, which shows a small mean negative value of 15 milligals over the eastern basin, in contrast to the mean positive value of about 15 to 20 milligals over the deeper western deep basin [Bowin, 1976; Committee for the Gravity Anomaly Map of North America, 1988] (Figure 14). These observations suggest that the eastern crust is both thicker and/or less dense than that of the western deep basin.

A possible explanation for this apparent anomaly is that eastern basin crust includes an upper layer of volcanics resting on the oceanic basement. This would explain the semi-continuous character of the basement horizon across both the rise and basin, as well as small scale similarities of basement relief between the eastern part of the rise and adjacent basin. The layer need not show a distinct internal reflection signature. The westward deepening of the eastern basin may reflect a westward thinning of this layer.

The irregular relief of the central seamount domain suggests that the topography has a volcanic origin. These seamounts

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Fig. 11. Multichannel seismic reflection profile (UTIG profile CT2-4) across the eastern deep basin domain. Other diagram elements are the same as in Figure 6. See the inset map and Figure 3 for profile location.
align with the lineament defining the eastern wall of the western deep basin, and may reflect "leakage" along faults during the opening of the western deep basin.

The nature of crust beneath the northwestern rise is unknown, as is its relationship to the adjacent eastern basin. The cross sectional pattern of basement faults on the south slope of the rise (Figure 9) suggests that this crust is rifted and thinned, but the strikes of these faults cannot be determined with present data. This basement may be a rifted western extension of the continental(? ) crystalline crust underlying the Isle of Pines [Somin and Millan 1977; Millan, 1981], which would imply that the Isle of Pines and related rocks of southwestern Cuba have a Caribbean origin rather than the North American origin proposed by Pardo [1975] and Gealey [1980].

The age of oldest crust within the eastern domains is a matter of conjecture. The minimum age is Late Cretaceous, as tonalites and granodiorites intruding the Cayman rise and ridge yield Late Cretaceous and Paleocene K/Ar cooling ages [Perfit and Heezen, 1978]. If the crust is contiguous with that of the Zaza terrane in Cuba, then it would be at least of Aptian-Albian age [Pardo, 1975; C.W. Hatten, O.E. Schooler, N. Giedt and A.A. Meyerhoff, Geology of central Cuba, eastern Las Villas and western Camagüey province, Cuba, unpublished report, 1958, hereinafter referred to as Hatten et al., 1958], and possibly as old as Late Jurassic [Iturralde-Vinent and Morales, 1988]. On the other hand, if a major convergence zone lay between the Zaza rocks and the Yucatan Basin, as implied by the Camagüey trench, then the maximum crustal age of the eastern Yucatan Basin is unconstrained.

Western deep basin crust. A variety of evidence shows that the western deep basin is underlain by oceanic crust. The Bouguer gravity field over the basin is oceanic in character [Bowin, 1976]. Models of free air gravity profiles across the basin indicate that crust underlying the deep basin has oceanic thickness (6 to 8 km) and density [Bowin, 1968; Dillon et al., 1972]. Seismic reflection profiles shot with high energy explosive sources show a persistent reflector at depths consistent with oceanic Moho (Figure 8). Depths of basement across the deep basins are oceanic [Rosencrantz et al., 1989] and the nested hyperbolic reflection patterns of the top of basement in the western deep basin are typical of ocean crust reflector patterns (Figure 8). Basin heat flow measurements [Epp et al., 1970; Erickson et al., 1972] are typical oceanic values. The basin contains magnetic lineations, although the NE-SW trending pattern of anomalies as mapped by Hall and Yeung [1980] and Yeung [1981] is inconsistent with underlying basement topography and structure and shows a poor match with known marine magnetics reversals sequences.

The deep basin is distinct in that it is rectangular in shape and in that the basement horizon is deeper than that of sur-
Fig. 13. Multichannel seismic reflection profile (UTIG profile CT2-10) across the eastern Cayman rise and Camaguey Trench domains. Diagram elements are the same as in Figure 6. See the inset map and Figure 5 for profile location.

The rectangular shape, faulted boundaries and deep oceanic basement of the western deep basin suggest that it formed as a small rift basin within older surrounding crust. Heat flow and depth to basement measurements indicate that the basin formed between 42 and 60 Ma (Middle Eocene to Late Paleocene) [Rosencrantz et al., 1989], as determined from the small basin cooling curves of Boernner and Sclater [1989]. If the basin simply represents a portion of a larger piece of typical ocean crust, then its heat flow and basement depth yield an older calculated age of between 55 and 75 Ma (Paleocene to Maastrichtian), based upon the crustal cooling curves of Parsons and Sclater [1977].

Basement Structure: Faults, Thrusts, and Sutures

The major offsets, lineaments and faults cutting the basement unit and horizon of the Yucatan Basin constitute three major tectonic structures. These are (1) the buried Camaguey trench located on the eastern boundary of the basin, (2) a broad, structurally complex paleo-transform fault zone...
between the Yucatan borderland and eastern crustal blocks, and (3) a long transcurrent fault that extends diagonally SW-NE across the eastern block.

**The Camagiiey trench.** In cross section the Camagiiey trench shows all the characteristics of a trench associated with a subduction zone (Figure 13). Basement clearly dips northeast beneath the Cuban margin. To the north the trench has been either truncated by, or truncated and offset along, La Trocha fault zone. To the south, it curves southeast toward the Cuban margin and Cauto depression. Whether it continues southeast beneath the margin cannot be determined. There is no direct evidence on the age or origin of the trench, and the tectonics of Cuba are not known well enough to fully constrain a mode of origin (see below).

**The transform zone.** The patterns of basement topography and structure within and adjacent to the Yucatan borderland and western deep basin indicate that this area includes a broad, north-south trending paleo-transform zone, or suture, between the Yucatan borderland and eastern crustal blocks. The zone extends from the southwestern corner of the basin northward to and including the Pinar fault of western Cuba, where it intersects the Cuban thrust belt. This transform defines the northwestern segment of the Late Cretaceous-Paleogene ("Laramide") suture along the Caribbean-North American plate boundary (Figure 1).

The basement topography of the Yucatan borderland outer ridge and escarpment, as seen in cross section (Figure 6) is similar in shape, size and internal structure to the present-day Cayman ridge and escarpment bordering the Cayman trough, and is interpreted as being of similar origin. As the base of the southern flank of the Cayman ridge defines the location and trend of the Oriente transform fault, so the base of the borderland scarp defines the location and trend of the paleo-transform fault. This is supported by free air and Bouguer gravity models of the pronounced, linear gravity low along the base of the slope, which show an abrupt westward thickening of crust (7 to 23 km) across the escarpment [Dillon et al., 1973; Bowin, 1976, Alvarado-Omana, 1986]. Seismic profiles across the base of the escarpment show little evidence for the presence of this fault, but this is expected in view of the roughness and dip of the basement horizon.

North of latitude 19.5° N, the western fault system includes two major, subparallel strands which merge northward as the Pinar Fault. Between latitudes 19.5° and 20° N, these two strands bracket a small pull-apart or rift basin. To the south, between latitudes 18° and 19.5° N, the fault zone in all likelihood includes the faulted and acoustically layered crust within the western deep basin adjacent to the escarpment, which might represent an exotic sliver of older crust emplaced within the transform zone.

The fault zone defining the eastern boundary of the western deep basin is not as well defined topographically, and shows no distinct gravity signature. The presence of multiple fault strands are likely, but not obvious. The zone extends north-
ward into the rough topography of the central seamounts domain, which may represent volcanics "leaked" along the fault zone during the early stages of its development. To the south, the eastern boundary appears confined to a narrow zone along the base of the low, linear topographic rise flanking the basin (see Figure 3), beyond which it disappears within the block faulting the southwest horst and graben domain.

The age of faulting, crustal rifting and basement deformation is Paleocene. As noted above, the probable age of western deep basin crust is Late Paleocene to Middle Eocene [Rosencrantz et al., 1989]. Late Cretaceous to Oligocene radiometric ages of basement metamorphic rocks dredged from the Yucatan borderland escarpment represent minimum ages [Pyle et al., 1973; Vedder et al., 1973], probably reset by an Eocene thermal event [Vedder et al., 1973]. Wells drilled in western Cuba penetrate series of platform sequence duplexes emplaced during Late Paleocene to Early Eocene time, and dated melange rocks in central and western Cuban indicate that the arc rocks of the Zaza terrane thrust over, and deformed, underlying sediments between Early and Middle Eocene time [Piotrowska, 1978; Pszczolkowski, 1978, Mossakovskiy and Albear, 1978; Pszczolkowski and Flores, 1986].

Transbasin fault. The long topographic lineament defined by the series of valleys, north facing escarpments, and structural discontinuities that extends SW to NE across the Yucatan basin marks the location of a large transcurrent fault. To the northeast this fault merges with and continues as La Trocha fault of central Cuba. To the west, the fault cannot be reliably traced beyond the point where it truncates the Cayman ridge.

The orientations of secondary (or splay) faults adjacent to the main fault (see the scarp at 20ø N, 82ø W, Figures 4 and 15), and offset of La Trocha fault [Pardo, 1975] both indicate that the sense of displacement is left-lateral. The amount of offset is small, probably less than 50 km, as suggested by the probable offset of La Trocha fault and the apparent offset of the north-south trending graben-like structure located at longitude 82.5ø W.

The age of the transbasin fault relative to transform faulting to the west is not clear. Displacement along La Trocha fault is commonly thought to have occurred during the Middle Eocene [Pardo, 1975]. There is evidence for northeast directed thrusting east of the fault during the Middle Eocene [Pszczolkowski and Flores, 1986]. This is younger than the ages (Paleocene, Early Eocene) attributed to faulting and thrusting in western Cuba, and would imply that the transbasin-La Trocha fault is younger. If so, this fault would support the argument of Malfait and Dinkiernan [1972] that the Caribbean plate, during its transition from northward to east-west movement, was attached to the North American plate through a process of "handing-off" pieces of Caribbean lithosphere. On the other hand, the apparent small offset across the fault would suggest that this process was limited and of short duration.

Other structures. The origin of the line of grabens between the Cayman ridge and the Cayman rise crest is unknown. They offset basement and lowest overlying sediments, so postdate the rise, but are apparently truncated by the Cayman ridge. Their development may reflect tectonic movement during the early stages of Cayman trough development.

The north-south trending topographic lineaments which cut the eastern basin and Cayman rise at longitude 82.5ø W probably represent a narrow graben of pre-Middle Eocene age. Whether it formed in response to transbasin faulting or to another earlier event is unknown.

The basement fault blocks characterizing the southwest horst and graben domain may have developed during Cayman trough opening. However, the block faults could also reflect local crustal extension related to movement on the transbasin fault, or represent a wide zone of north-south trending slip faulting related to transform displacements.

Sediments that fill the Yucatan basin are largely undisturbed, indicating that the basin has undergone little deformation since its formation. Exceptions include the folding of deep sediments along the Camagüey trench, the faulting of deep sediments along the line of grabens south of the Cayman rise, both noted above, and minor faulting and tilting of sediments along the southern edge of the basin, adjacent to the Cayman trough. Seismic reflection profiles across the easternmost Cayman ridge show small graben-like structures within sediments capping the ridge. Much of the Cayman ridge has been displaced vertically during the Neogene [e.g., Perfitt and Heezen, 1978], although this is not discernable on seismic profiles. To the west, faulting and slumping of sediments and tilting of reefs [Stoddart, 1962] along the southern Yucatan borderland indicate that this part of the margin is tectonically unstable at present [Dillon and Vedder, 1973]. Elsewhere, sediments overlying the transcurrent fault south of the central seamounts (Figure 10, kilometers 105 and 130) exhibit evidence of tilting and faulting; these probably reflect local and limited reactivation of the transbasin fault.

Regional Implications

Preserved basement structures of the present-day Yucatan Basin (Figure 15) provide a snapshot of Eocene tectonic conditions in the northwestern Caribbean. Plate motions inferred from fault and rift orientations are consistent with known structure of the Cuban thrust belts [e.g., Pardo, 1975]. The timing of rift basin opening [Rosencrantz, et al., 1989] correlates with that of Cuban thrusting [e.g., Pszczolkowski and Flores, 1986], and the amount of opening of the rift basin(s), about 350 km, provides a minimum estimate of the amount of Eocene thrusting in Cuba.

This 350 km represents only the final phase of the total northward movement of the Yucatan-Cuban blocks relative to the Bahamas platform. Reconstructing the basin by closing the rifts (Figure 16) places the Zaza terrane adjacent to the Yucatan platform. Because the history of the eastern Yucatan platform records no (or insignificant) volcanics [e.g., Lopez-Ramos, 1975], the Zaza terrane must have moved from a location further south. Assuming that the Santa Cruz ophiolite in Guatemala [Rosenfeld, 1980] represents a fragment of the western continuation of the Zaza terrane, then the total minimum displacement of the terrane since the emplacement of the Santa Cruz ophiolite in Campanian time has been about 1100 km.

Both the location and structure of the pre-Eocene plate boundary between the basin and Yucatan platform are unknown at present, as is the question of why the boundary
Fig. 15. Tectonic interpretation of Yucatan Basin seismic geology.
developed pull-apart or rift structures during the Late Paleocene or Early Eocene. One possible answer is that as the leading edge of the northward moving Yucatan basin-Cuban lithospheric block "felt" the approaching Bahamas platform, it was nudged eastward so as to rotate the blocks in a clockwise sense. This would reorient and "open" the strike-slip boundary along the western edge of the block. As new faults developed to accommodate the new motion, the fault zone would widen and existing faults would extend so as to initiate "leaky" volcanism. This would be consistent with the volcanics proposed for the northeastern corner of the western deep basin.

The apparent lack of a time gap between the Middle Eocene cessation of Caribbean-North American convergence, as recorded by Cuban thrusting [e.g., Pardo, 1975; Pszczolkowski and Flores, 1986] and the Middle Eocene opening of the Cayman trough [Rosencrantz et al., 1988] raises the possibility that east-west strike-slip displacement between the Caribbean and North American plates began before or during Cuban-Bahamas thrusting, rather than after. East-west displacement must have started prior to the Middle Eocene if Cayman trough spreading represents a mature phase of pull-apart rifting. If so, then the Yucatan basin-Cuban block was detached from the Caribbean plate before the block had fully converged on the Bahamas platform. The relative displacements recorded by the basin transforms and rifts represent the displacements of that block relative to the North American plate, not those of the Caribbean plate (as represented by the Nicaragua Rise, Colombian Basin and Venezuelan Basin) relative to the North American plate.

Additional questions about the Cretaceous plate bean lithosphere. On the other hand, the apparent small offset across the fault would suggest that this process was limited and of short duration.

Other structures. The origin of the line of grabens between the Cayman ridge and the Cayman rise crest is unknown. They offset basement and lowest overlying sediments, so postdate the rise, but are apparently truncated by the Cayman ridge. Their development may reflect tectonic movement during the early stages of Cayman trough development.

The north-south trending topographic lineaments which cut the eastern basin and Cayman rise at longitude 82.5° W

Fig. 16. Eocene plate reconstruction of the Yucatan Basin.
probably represent a narrow graben of pre-Middle Eocene age. Whether it formed in response to transbasin faulting or to another earlier event is unknown. The basement fault blocks characterizing the southwest horst and graben domain may have developed during Cayman trough opening. However, the block faults could also reflect local crustal extension related to movement on the transbasin fault, or represent a wide zone of north-south trending strike slip faulting related to transform displacements. Sediments that fill the Yucatan basin are largely undisturbed, indicating that the basin has undergone little deformation since its formation. Exceptions include the folding of deep sediments along the Camagüey trench, the faulting of deep sediments along the line of grabens south of the Cayman rise, and both noted above, and minor faulting and tilting of sediments along the southern edge of the basin. Adjacent to the gence zone is the uplifted and exposed Trinidad thrust fault in south-central Cuba [Hatten et al., 1958; Hatten, et al., 1988]. The right-lateral offset of the zone across La Trocha fault is apparent and due to crustal uplift west of La Trocha fault. To the southeast the convergence zone lies buried beneath the younger sediments and volcanics of the Cauto depression and Sierra Maestra.

SUMMARY

The distribution of basement types and the pattern of faulting shown by Yucatan Basin seismic reflection profiles indicate that the basin includes crusts of three different compositions and origins:

1. Crust underlying the western edge of the basin (Yucatan borderland domain) represents the eastern, offshore continuation of the adjacent Yucatan platform section. Basement rocks probably include Cretaceous carbonates and evaporites, Jurassic red beds and Paleozoic crystalline rocks similar to those sampled on the platform. Sediments filling the troughs and basins of the borderland likely represent facies equivalents of platform carbonates of middle and late Tertiary age. Basement beneath the southwestern corner of the basin (southwestern horst and graben domain) may include stretched platform crust.

2. Topographically heterogeneous crust underlying the eastern two-thirds of the basin (eastern Cayman rise, Cayman ridge, and Camagüey Trench domains) includes a thick sequence of volcanics and plutonics in the form of the Cayman rise. With the exception of the Cayman ridge, the basement topography predates basin formation. Volcanics are Late Cretaceous to Eocene? in age, and rest on older crust, of unknown age, of probable oceanic origin. The eastern edge of the basin is thrust beneath the Cuban margin; its structural relationship with the Cuban platform elsewhere is not known.

3. The rectangular basement deep underlying the western third of the basin is a pull-apart basin formed within the transform boundary separating the Yucatan platform and eastern basin. Available evidence demonstrates that the deep is oceanic, and probably formed during the Late Paleocene to Middle Eocene.

The Yucatan platform is separated from oceanic crust beneath the eastern Yucatan basin by a paleo-transform boundary, which defines the northwestern portion of the Caribbean-North American convergent plate boundary. This zone includes a large pull-apart basin, floored with oceanic crust. The orientations of this basin and related fault trends show that displacement across the transform was left-lateral, with the eastern Yucatan basin and attached Cuban section moving N to NNE relative to a fixed Yucatan platform. The amount of offset, as estimated from the length of the pull-apart basin, is about 350 km, not including displacement accommodated by crustal stretching and thinning. The best estimate of age of displacement is Late Paleocene to Middle Eocene.

The eastern edge of the Yucatan basin has been thrust beneath the Cuban margin along a now-buried trench, called the Camagüey trench. This structure may have formed as an Eocene backthrust behind the Cuban arc, or it may represent a remnant of the Cretaceous subduction system associated with the Cuban arc (Zaza terrane). The trench is truncated at its north end by a long, left-lateral fault which extends SW-NE diagonally across the basin and continues onland in central Cuba as La Trocha fault.

The basement topography of the Yucatan basin gives a picture of the Eocene tectonics of the basin and permits a reasonable reconstruction of basement structure during Late Paleocene or Early Eocene time, but yields little information as to the pre-Eocene tectonics of the western Caribbean. However, the close timing between the finish of Yucatan basin-Cuban northward motion and the start of Cayman trough east-west strike-slip motion suggests that the two events may have overlapped.

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