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Seismic Structure and Stratigraphy of Northern Edge of Bahaman-Cuban Collision Zone[1]

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ABSTRACT

Common-depth-point (CDP) seismic reflection data in the southwestern Bahamas reveal the northern edge of the tectonized zone that resulted from the late Mesozoic–early Cenozoic collision of Cuba and the Bahamas. Two seismic facies are present: a basin facies and a shallow-water carbonate-platform facies. In Santaren Channel, between Cay Sal and the Great Bahama Bank, a 5-sec thick group of coherent flat-lying reflections is inferred to represent an accumulation of deep-water basinal carbonate deposits approximately 10 km thick. At the southern end of Santaren Channel and in Nicholas Channel toward the west, the basinal carbonate section thins abruptly and overlies zones that lack coherent reflections. These structureless zones, which are attended by positive gravity anomalies, are inferred to represent shallow-water carbonate-platform materials. Neither seismic facies has associated short wavelength magnetic anomalies.

A 10-km broad anticline occurs at the south end of Santaren Channel. Platform carbonates in the core of this structure overlie Early Cretaceous and older basinal carbonate deposits and are onlapped by Late Cretaceous and Cenozoic basinal facies. The structure is inferred to be a hanging-wall anticline at the northern limit of the Cuban fold-thrust belt formed in the Late Cretaceous. In eastern Nicholas Channel, a 40-km broad, tilted block of platform carbonate material appears to have been uplifted prior to the latest Cretaceous. This feature is onlapped by Upper Cretaceous and Cenozoic deposits. A depositional-erosional carbonate-platform edge of Early Cretaceous age occurs in western Nicholas Channel at its juncture with the Straits of Florida. An Early Cretaceous platform margin at this location indicates that a deeper water embayment extended northward into the Straits of Florida, around northern Cay Sal Bank, and back into Santaren Channel during the Early Cretaceous.

INTRODUCTION

This paper presents geophysical data obtained in the western reaches of the Old Bahama Channel separating Cuba and the Bahamas (Figure 1). This location lies between the relatively stable Florida-Bahamas carbonate province and the Cuban subduction zone marking an ancient North American–Caribbean plate boundary (Figure 2). Our main conclusion is that measurements reveal the northern edge of the tectonized zone related to the collision of the stable carbonate province and the Cuban arc.

PREVIOUS WORK

Meyerhoff and Hatten (1968) clearly illustrated Cuba's general geology. From their synthesis, Cuba appears to be composed largely of Mesozoic rocks. The oldest igneous and metamorphic rocks are on the south; northward, igneous and metamorphic rocks are bordered by volcaniclastics that contain displaced serpentinites and gabbroic complexes, which are in turn flanked by predominantly carbonate rocks and evaporites (Figure 2A, B). The serpentinites are concentrated by flowage in a median welt that extends the length of the island and roughly separates the volcaniclastics on the south from the carbonates and evaporites on the north. The welt is the locus of a regional gravity minimum, probably reflecting the low density of the serpentinites. These altered basic igneous rocks constitute an ophiolite suite (Gealey, 1980) that is thought to have resulted from consumption of former oceanic crust in the Cuban subduction zone.

All pre-middle Eocene rocks have been folded and thrust toward the north (Figure 2A-D). Northeast-trending, left-lateral, strike-slip faults offset thrust sheets and appear to agree in position with left-lateral offsets of the present coastline. Serpentinite flow along major thrust-fault planes is inferred. Salt flow on thrusts in the northern carbonate province, with attendant diapirism, is documented by drilling (Figure 2C, D). Different rock types are commonly in fault contact, and intrusions are abundant.

Furrazola-Bermudez et al (1964) and Tator and Hatfield (1975a, b) described the lithologies and ages of sediments

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The data on which this report is based were collected on the R/V *Gilliss* of Rosenstiel School of Marine and Atmospheric Sciences (RSMAS), University of Miami, in September 1979. The scientific party included members of USGS, Woods Hole Oceanographic Institute (WHOI), and RSMAS. The original reflection time sections were generated by Phillips Petroleum Company in Bartlesville, Oklahoma.

We thank several oil company colleagues whose comments on drafts of this paper resulted in improvements. Among them, R. A. Dorsey of Exxon, J. A. Drahovzal of Gulf, and R. E. Erlich of Amoco made important corrections and contributions to the understanding of our data. A. A. Meyerhoff, despite disagreements with some of our conclusions, did a superlative job of editing for us and unquestionably improved the paper's accuracy, clarity, and completeness. Finally, we thank our colleagues at USGS: W. P. Dillon and K. D. Klitgord who also made major corrections and additions in their editorial analysis of earlier drafts, and J. S. Schlee, D. W. O'Leary, and E. A. Winget who reviewed the final effort.

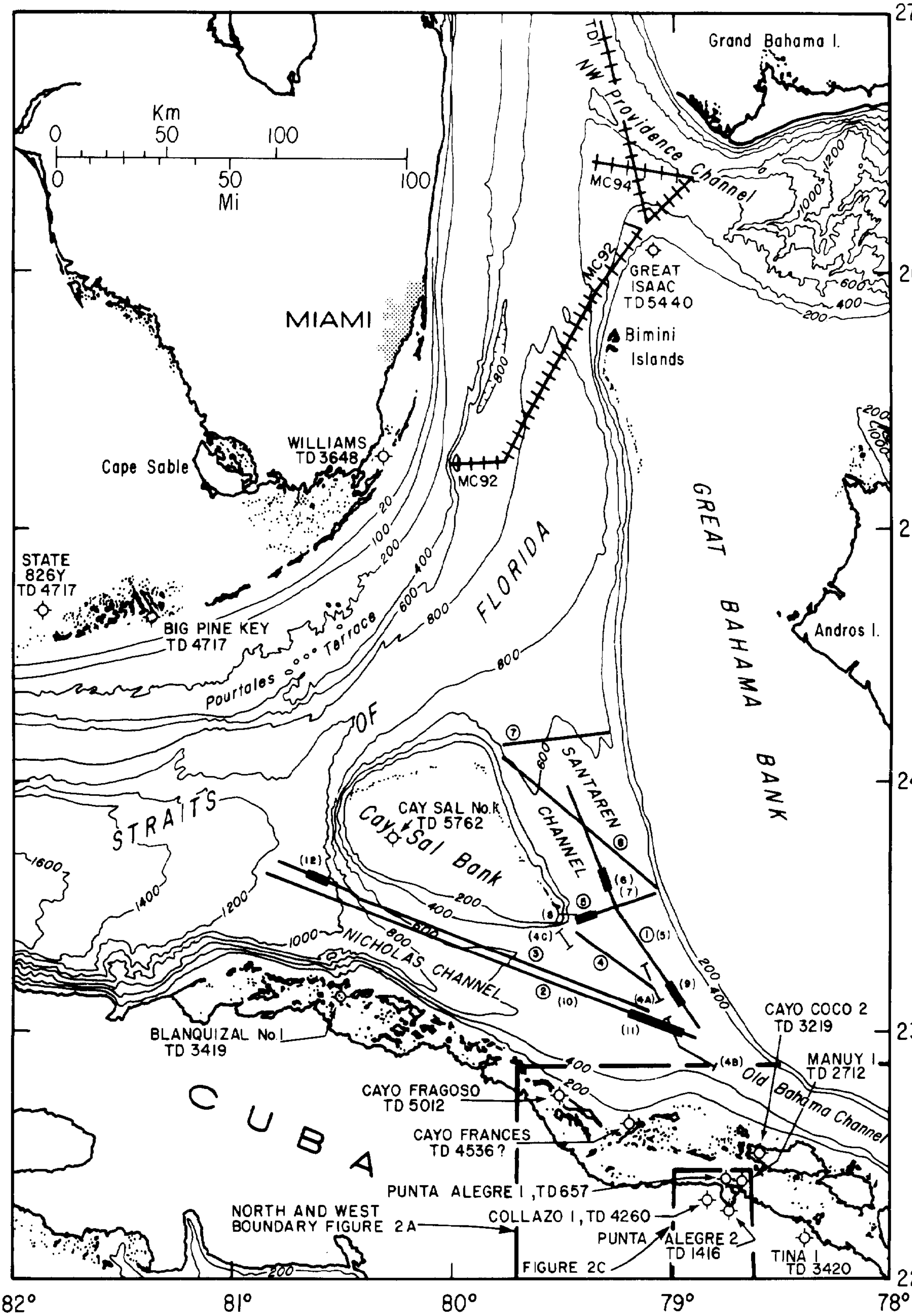


Figure 1—Index map with bottom topography contoured in meters (C.I. = 200 m). (From Sorenson et al, 1975.) Well depths are in meters. Circled numbers designate our seismic lines. Numbers in parentheses refer to figures in text. Thick bars represent detailed time sections of portions of these data. Lines with crossed ends (numbered 4A, 4B, and 4C) show locations of single-channel lines from Idris (1975). Hachured lines labeled MC92 and MC94 are from Sheridan et al (1981). Hachured line labeled TD 1 is from Dillon et al (1979).

penetrated in several deep wells along Cuba's north coast (Figure 1). These data, summarized in Figure 3, show that Jurassic and Cretaceous carbonates and evaporites predominate in the northern coastal zone. Judging from published picks (Figure 3), Late Cretaceous–early Cenozoic and mid-Cretaceous unconformities are inferrable in more than half of these wells. Elevations on correlative picks range widely. Repeated sections occur in some wells (e.g., Manuy 1), indicating that the fold-thrust belt seen in outcrop continues northward to the coast.

Pardo (1975) presented details of the various facies and structural styles encountered in the belts that strike more or less along the length of the present island. From Pardo's descriptions, the carbonates of the north coast include shallow-water platform and basinal types, with evaporites in the Upper Jurassic and Lower Cretaceous. Pardo (1975) pointed out that the carbonate facies of onshore Cuba are similar to those in the present Bahamas. That is, they suggest the presence of shallow platforms separated by deep-water tongues.

Based on the distribution of continental and oceanic metamorphic rocks and the distribution and age of volcanic rocks in the Greater Antilles, Mattson and Pessagno (1979) posed the possibility of an initial northward-dipping subduction zone during the Late Jurassic and Early Cretaceous. According to these authors, the collision of the northbound buoyant continental crust with this early subduction zone stopped crustal consumption on the south, but continued compression resulted in a new southward-dipping subduction zone on the northern margin of the older arc (Mattson and Pessagno, 1979). The northward convexity of the Cuban arc, together with the northward transport of thrust sheets in Cuba, reflect the existence of the southward-dipping subduction zone beneath the north coast.

A synthesis of the geologic history of the Florida-Bahamas-Cuban region is included in Klitgord et al (1984). According to these authors, the major tectonic units of this area are bounded by fracture zones. The Klitgord et al "Cuban fracture zone" now lies along the northern coast of present-day Cuba. This feature was the site of early left-lateral motion of the North American plate relative to the South American plate. Judging from the orientation of thrust faults in Cuba (Figure 2A), the relative motion of the Cuban arc was toward the north-northeast. Plate reconstruction indicates that the North American plate moves toward the northwest. Therefore, the Bahaman-Cuban collision may have been a sideswipe in a convergent strike-slip fault zone.

Marine geophysical investigations indicated the existence of tectonism in the Old Bahama Channel off Cuba's north coast. Using single-channel data, Idris (1975) discovered buried, tilted blocks with apparent widths of 10 to 40 km and reliefs of at least 1 km (Figure 4A, B). The blocks rise to within a few hundred meters of the sea floor. They show some indication of internal stratification in their upper few tenths of a second, although they generally lack good deeper coherent reflections. These blocks occur in a region of 5.9 km/sec refraction velocity at depths only slightly greater than 2 km (Sheridan et al, 1966) and lack any magnetic anomaly. Because of this, Idris (1975) inferred them to be cemented, shallow-water carbonate-platform material buried in unconsolidated sediments. Idris also detected a possible diapir with an apparent width of 1.5 km, rising to within 100 m of the sea floor just southeast of the southeast corner of Cay Sal Bank (Figure 4C). The presence of evaporites in the section, with attendant diapiric tectonism, represents a potential for further structural complication in this region.

In summary, Cuba is a pre-middle Eocene convergent plate boundary with a subduction history that includes consumption of former oceanic crust. Plate reconstruction suggests elements of left-lateral, strike-slip faulting in the convergent zone. A northbound, fold-thrust belt related to the subduction zone extends into the offshore area of northern Cuba. The rocks involved in the northern part of this fold-thrust belt are predominantly Mesozoic carbonates that contain both shallow platform and deep-water facies. These facies are similar to those seen in the present-day Bahamas. Tilted blocks in the offshore subbottom indicate that the northern edge of Cuban tectonism extends to the junction of Santaren, Nicholas, and Old Bahama Channels. The presence of evaporites onshore and their inferred presence in the adjacent offshore indicate salt tectonism may complicate offshore structure. The purpose of our survey was to reveal details of this offshore structure, using multichannel seismic, magnetic, and gravity data.

EQUIPMENT

The seismic system consisted of a digital recorder with automatic gain ranging over a 500-msec window, a 12-channel hydrophone streamer 1,100 m long, and an air gun. The recording sampling interval was 4 msec. Record length was 5-6 sec when a 550-in.^{3} air gun served as the energy source, and 3 sec when a 40-in.^{3} gun was employed. The distance from the gun to the center of the farthest active element was 1,415 m. Shot points were 50 m apart in order to obtain a 12-fold stack. A complete description of all processing sequences is contained in Taylor et al (1983).

Navigation was supplied by a Western Geophysical Survey and Data Management System, using a Hewlett-Packard 2112 minicomputer and interface circuitry to integrate data from six navigation sensors. Two types of sensors were used: (1) velocity output, including range-range loran, doppler (continuous) sonar, and gyroscope; and (2) position output including navigation satellite receiver and a hyperbolic loran. The navigation system triggered the seismic-system air guns at 50-m intervals and fed velocity information to a Bell Aerospace BGM-3 gravimeter. A Lacoste-Romberg (LR) seagoing gravimeter and recording system was used for backup and for cross-checking against the Bell meter. Both the LR and Bell data were recorded on the navigation tape, and the LR data were processed together with post-cruise analysis of the navigation information to produce track charts and gravity profiles.

In addition to CDP seismic and gravity data, total field magnetic measurements were obtained using a Varian proton magnetometer. High-resolution seismic data were also recorded using a single-channel streamer, analog recorder, and 5-in.^{3} air gun.

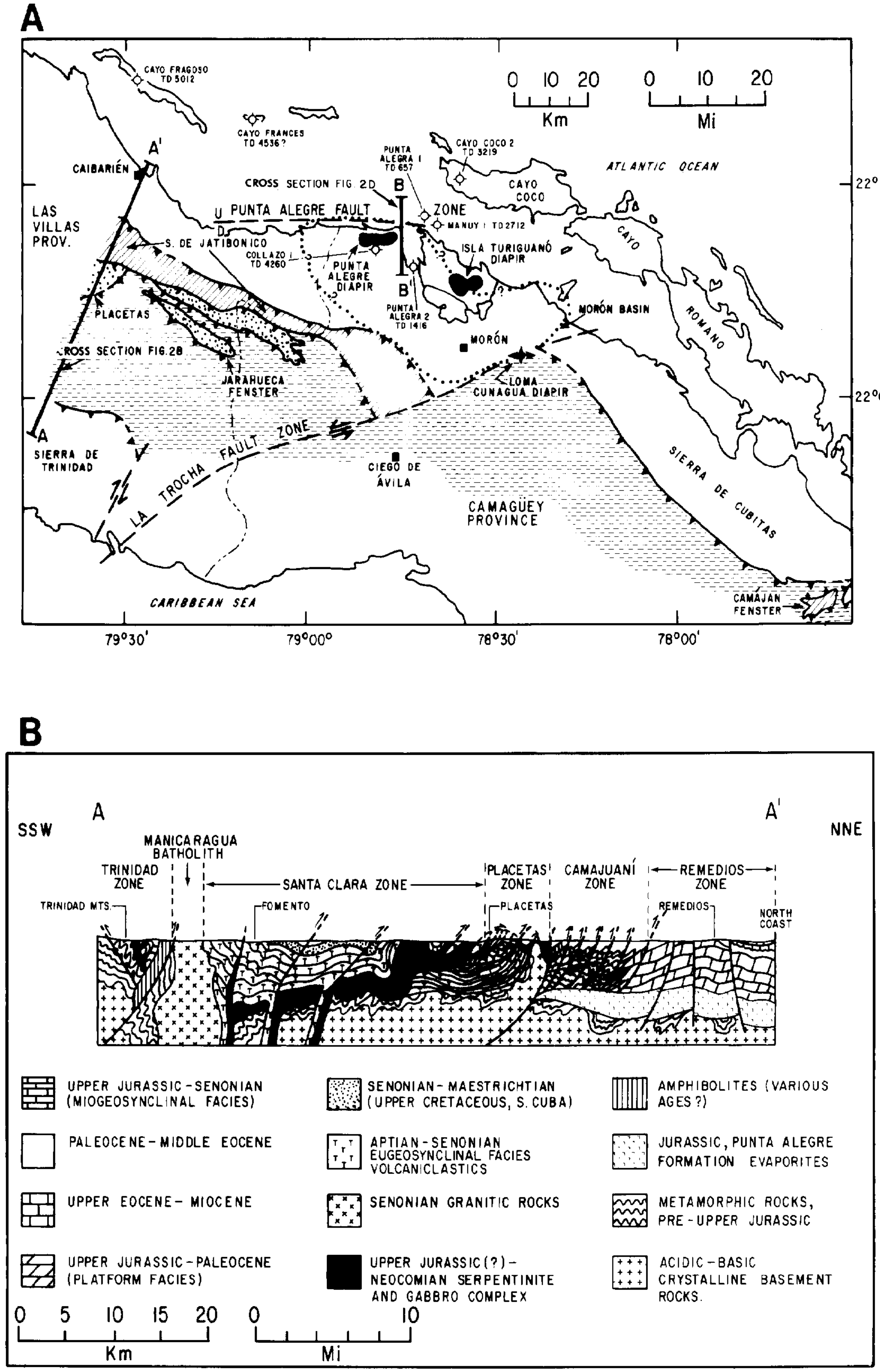
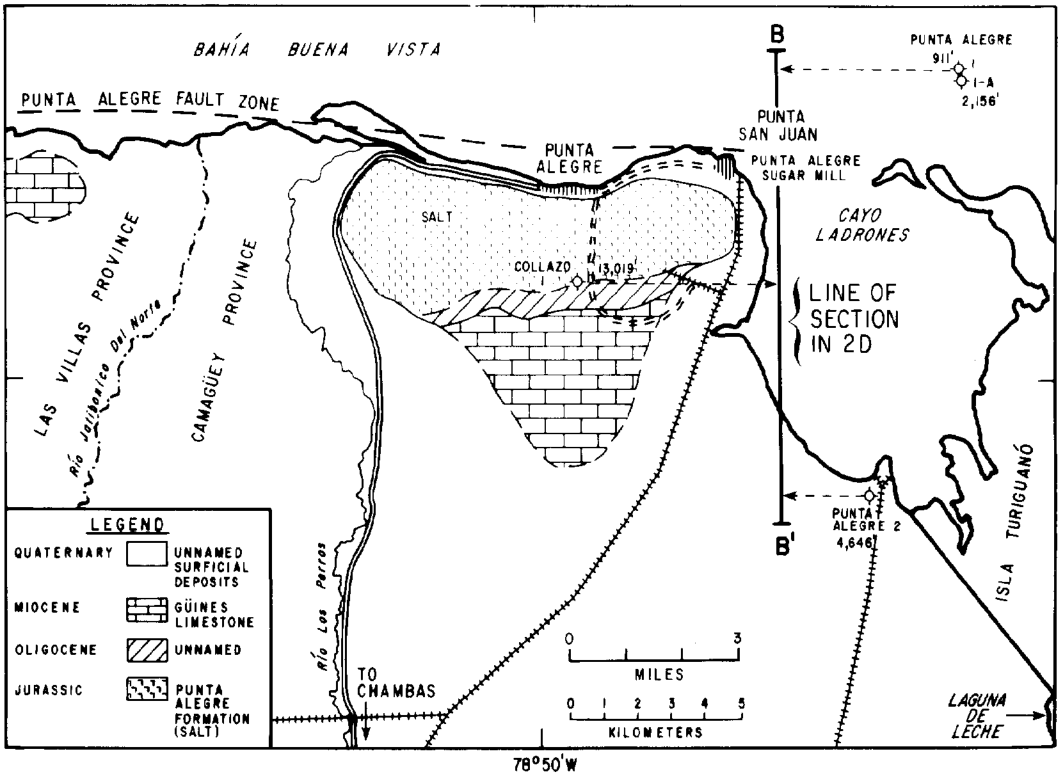


Figure 2—(A) Geologic map and (B) cross section from Meyerhoff and Hatten (1968) showing major structural features of onshore Cuba adjacent to our offshore study area. (C) Local geologic map and (D) cross section from Meyerhoff and Hatten (1968) showing salt diapir in north coastal zone of Cuba adjacent to our offshore study area. See A for regional location of this feature. (B is modified from Ducloz and Vuagnat, 1962; Wassall, 1957.)

C



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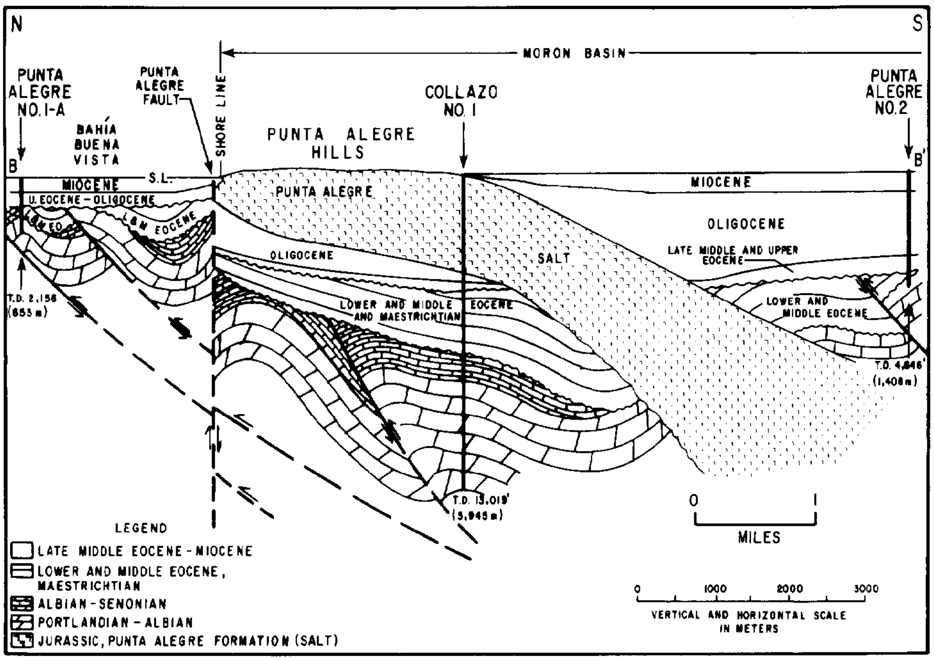

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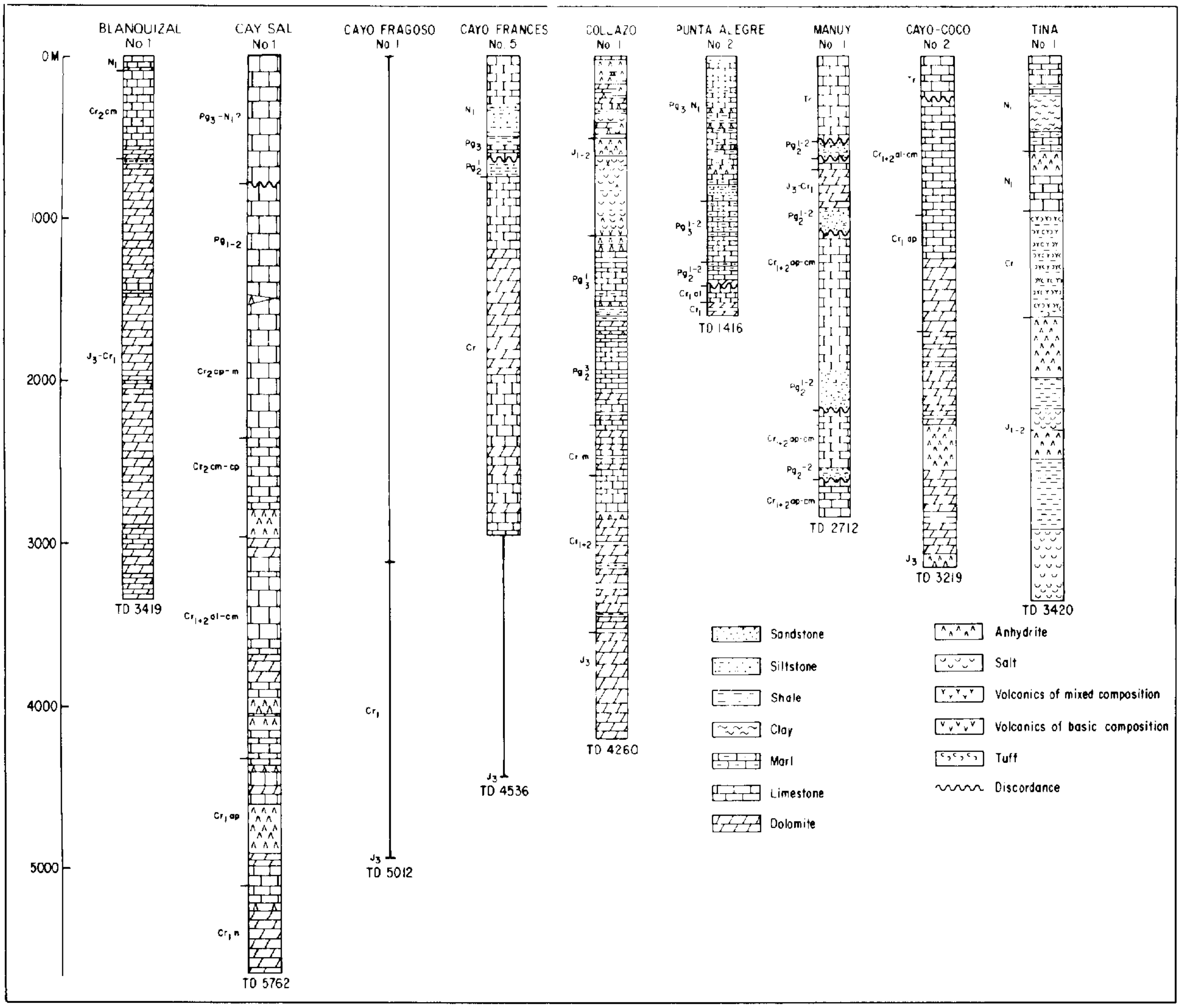

Figure 3—Stratigraphic sections based on deep wells in Cuba and Cay Sal. These data are taken from compilations of oil company data by Furrazola-Bermudez et al (1964) and Tator and Hatfield (1975a, b). Symbols are as follows: J_1 = Early Jurassic; J_2 = Middle Jurassic; J_3 = Late Jurassic; C_1 = Early Cretaceous; C_2 = Late Cretaceous; Pg = Paleogene; N = Neogene; and Tr = Tertiary. Lowercase letters indicate Cretaceous stage names: n = Neocomian; ap = Aptian; al = Albian; cm = Cenomanian; cp = Campanian; and m = Maestrichtian. Well locations are shown on Figure 1.

SEISMIC REFLECTION MEASUREMENTS

Regional aspects of our study are described with reference to horizontally squeezed record sections. The increased vertical exaggeration of these sections enables detection of subtle structures and augments coherence of some reflections. These regional sections illustrate major structures and seismic lithostratigraphic and time-stratigraphic units. Records at normal time scale are keyed to the squeezed sections and used to show details of interest. The initial figure presenting squeezed section data (Figure 5) is labeled with values of vertical exaggerations. The horizontal scale of our sections is 5 km = 100 shot points (SP).

The age assignments indicated in the margins of our seismic sections are based on correlations of reflection time and character with seismic data from Dillon et al (1979) and Sheridan et al (1981). The Dillon et al (1979) survey tied the COST GE-1 well off Jacksonville, Florida. The key correlation is the mid-Cretaceous event (MKE), a strong reflection at about 2.3 sec (Figure 5) that can be seen on all of our lines over the basinal portion of Santaren Channel (Figure 1). This event is also a strong reflection in Dillon et al (1979) data over the Blake Plateau and can be followed to the extreme southern extent of his survey just off the northwest corner of the Great Bahama Bank. Sheridan et al (1981) data tied the Dillon et al (1979) survey on the axis of the Northwest Providence Channel, just north of the Great Isaac well (Figure 1). The Sheridan et al (1981) lines extend southward in the Straits of Florida to northern Key Largo (Figure 1), about 70 nmi north of our line 7 in Santaren Channel. At the COST GE-1 well, the MKE reflection has been related to the seismic impedance contrasts associated with a mid-Cretaceous unconformity marked by Turonian silty shales overlying a 100-ft thick zone of lignitic conglom-

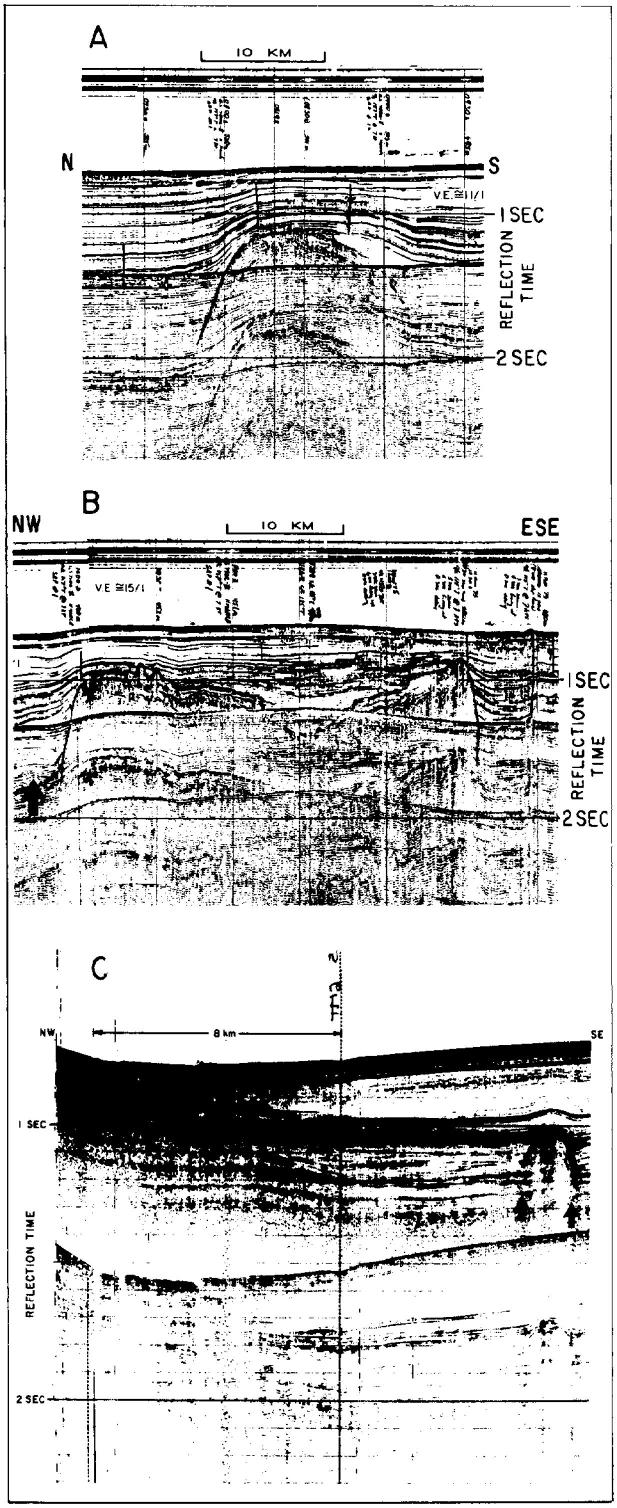

Figure 4—(A and B) Structures revealed by single-channel, 40-in.^{3} air-gun data from Idris (1975). These structures are located at 4A and 4B in Figure 1. Two structures seen in B are separated by course change and probably represent single block bounded by fault scarp on north and east. (C) Possible salt diapir (from Idris, 1975) southeast of Cay Sal at 4C on Figure 1. These data were collected using a 40-in.^{3} air-gun system. Vertical exaggeration in sediment section is approximately 10×. Arrows indicate inward-dipping reflections marking outer edges of possible rim syncline.

eratic sands that, in turn, overlie Albian shelf carbonate rocks (Dillon et al, 1979).

As mentioned earlier, owing to structural complications, elevations on various correlative stratigraphic intervals in onshore Cuban wells vary widely (Figure 3). It follows that the well elevations are of no use in determining the time-stratigraphic significance of reflection sequences in adjacent offshore seismic profiles.

Essentially two seismic facies are revealed in our data. The first consists predominantly of strong, planar, continuous bands of reflections in basinal settings. This reflection pattern is common in deep water where the constant rain of pelagic tests is intermittently interrupted by layers of allochthonous shallow-water carbonate material swept into deeper water areas during storms. Where storm layers are lacking, reflections fade and the resulting whitened translucent bands correlate with chalk units. The second seismic facies typically has a strong, rough reflection at its upper surface and generally lacks coherent internal reflections. This facies borders the basin facies in Santaren Channel and can be traced from beneath the basin facies updip to positions where it crops out on the sea floor and emerges as the present platform edge. The basin facies typically onlaps the platform facies. The platform facies has associated positive gravity expression, no magnetic signature, and high interval and refraction velocities characteristic of shallow-water carbonate-platform rock.

The description of seismic reflection data that follows is arranged according to geographic settings: (1) Santaren Channel; (2) the transition from Santaren Channel's deep basin to shallow platform rock at the junction with Nicholas Channel; and (3) Nicholas Channel, with its uniformly shallow occurrence of platform rock buried by an onlapping thin cover of deeper water carbonate sediment.

SANTAREN CHANNEL

Figure 5 shows the squeezed section of line 1 (Figure 1). On the left or northern part of the profile, coherent reflections can be carried to the full length of the record (i.e., 5 sec), which according to velocity analyses represents a depth of about 10 km. Above 3 sec, to a depth of about 5 km, moveout variations between primary reflections and multiples are sufficient to identify reflections as primaries. Below 3 sec, some multiples occur.

Uniform reflection character is typical of all of line 1 north of SP 2000. A 10-km broad, low-relief anticline (Figure 6) interrupts the continuous and essentially flat reflections between SP 700 and 900. The feature has a relief of about 0.1 sec or 200 m on the MKE. Several amplitude anomalies occur over the crest of this structure. Subtle, low-relief structures like the one shown in Figure 6 are typical for the Santaren Channel axis. The structure appears to have affected the entire Cretaceous and older section, and may be related to a deep flexure beneath its steeper southern margin. The same relatively flat and coherent reflection character is present on lines 5, 6, and 7 (Figure 1), except at their ends where they are in close proximity to shallow bank edges. The MKE at 2.3 sec (Figure 5) is about 3 km deep.

At the western end of line 5, a disturbed zone of incoherent reflections appears as a block below 2 sec (Figure 7). The

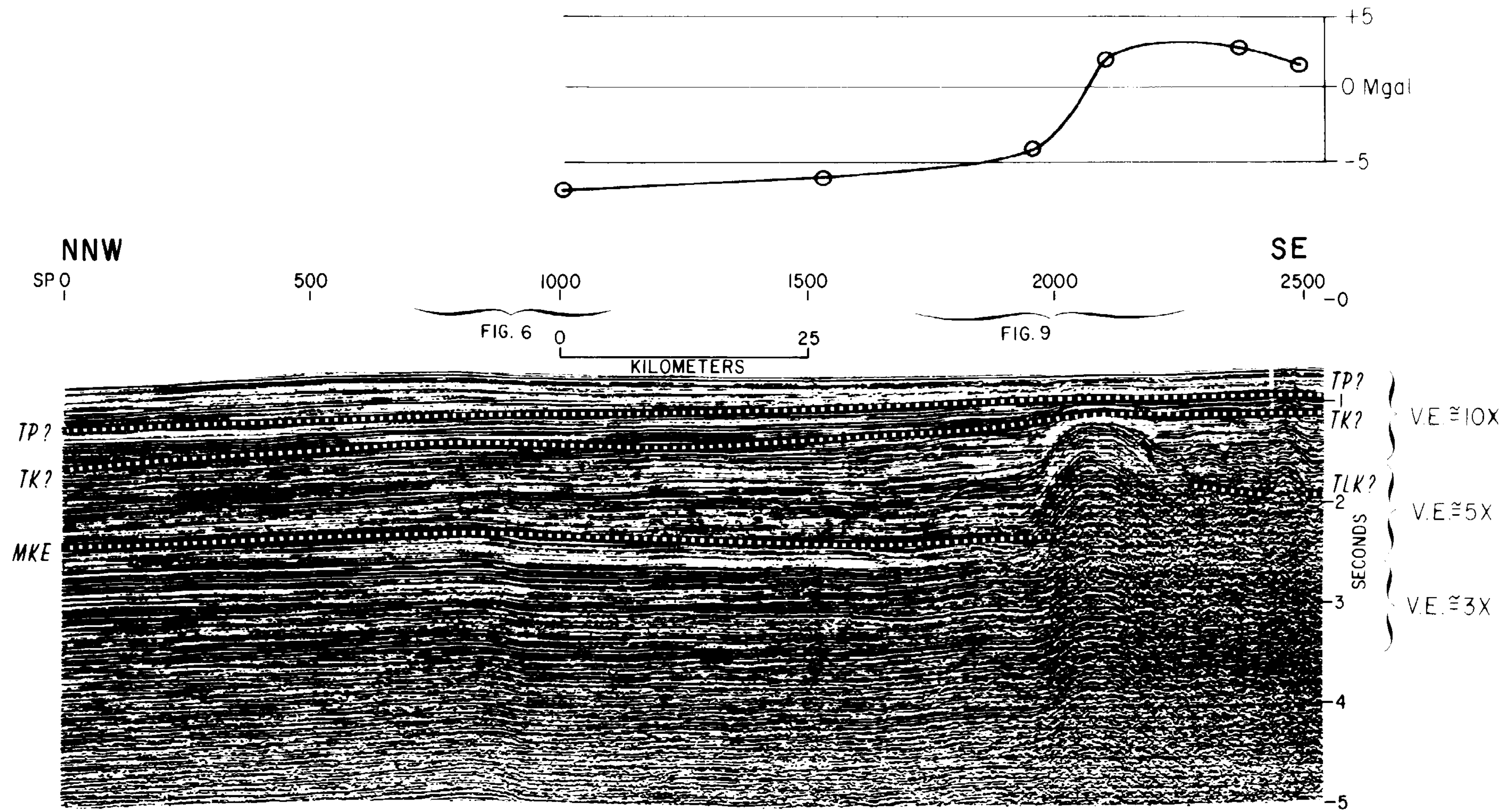

Figure 5—Horizontally squeezed time section of line 1 (see Figure 1 for location). In this and succeeding sections, north and west are on left. Shot points (SP) are indicated at upper margin. 100 SP = 5 km. Vertical scale is in seconds. A few prominent reflections are marked, and tentative stratigraphic horizons are indicated. MKE = an inferred mid-Cretaceous event in basin facies; TLK = inferred top of Lower Cretaceous platform rocks; TK = inferred top of Cretaceous rocks; and TP = inferred top of Paleogene section. Approximate vertical exaggerations are indicated for succeeding 1-sec intervals of subbottom penetration. Coherent characters of reflections to full recording time of 5 sec, north of SP 2000, mark velocity and density contrasts in basinal carbonate sediments of Santaren Channel. To the south, a large anticline (10 km broad) occurs at transition from continuous reflections at depth to zone (below 1.8 sec) lacking coherent reflections. Zone of incoherent reflections is attended by positive free-air gravity anomaly shown in upper margin and has no magnetic signature. For these reasons, this reflection character is inferred to represent shallow-water carbonate-platform rocks. Figures that provide details of significant local structures are indicated in upper margin.

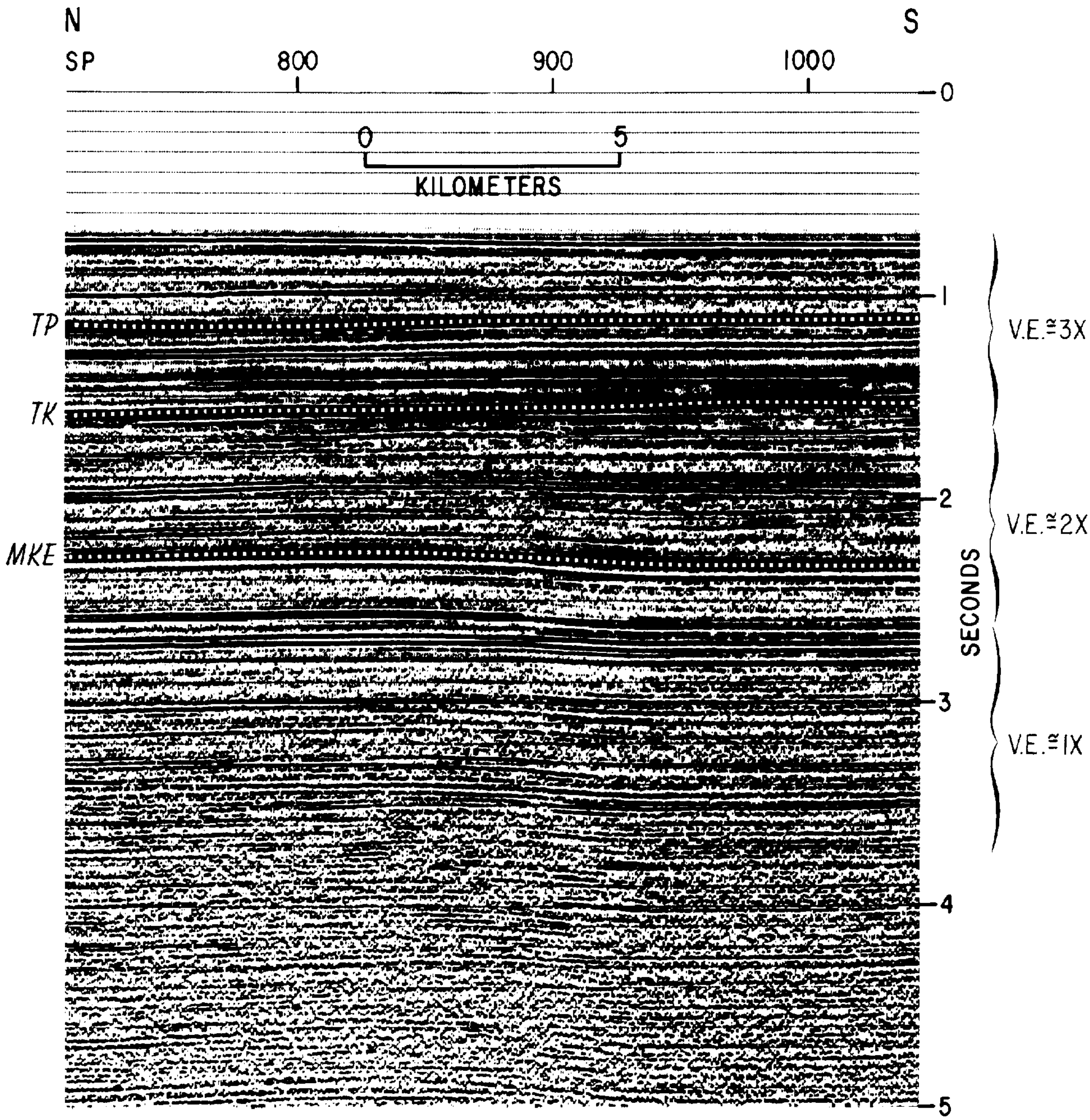

Figure 6—Enlarged segment of line 1 showing a broad, low-relief dip reversal that occurs between SP 800 and 900. Apparent relief on this feature is 100-200 m; breadth is 5-10 km. Feature may result from flexure over deeper fault.

block of platform material ends abruptly near SP 70, where continuous reflections of the basinal section terminate at a steeply dipping contact (Figures 7, 8). Diffractions, terminations, and dip changes at the contact may indicate the presence of a fault, or the platform slope may have been oversteepened by erosion. East of the platform to basin transition, highly reflective basinal carbonates occur to the full recording time of 3 sec (about 5 km). The mid-Cretaceous event stands out at 2.3 sec. A dip reversal with a breadth of almost 10 km and relief of less than 100 m on the MKE occurs between SP 360 and 540 (Figure 7). Relief on this feature is expressed up to and including the sea floor. Lines 6 and 7 are similar to line 5. All of the sections seen on these lines contain coherent reflections of probable basinal carbonates. The MKE event can be traced over the full extent of these lines.

JUNCTION OF SANTAREN AND NICHOLAS CHANNELS

A distinguishing feature of the anticlinal structure between SP 2000 and 2200 (Figures 5, 9) is its location above an abrupt transition. On its north, continuous reflections occur to 5 sec of reflection time. South of the structure, coherent reflections terminate at 1.3 sec above a sequence

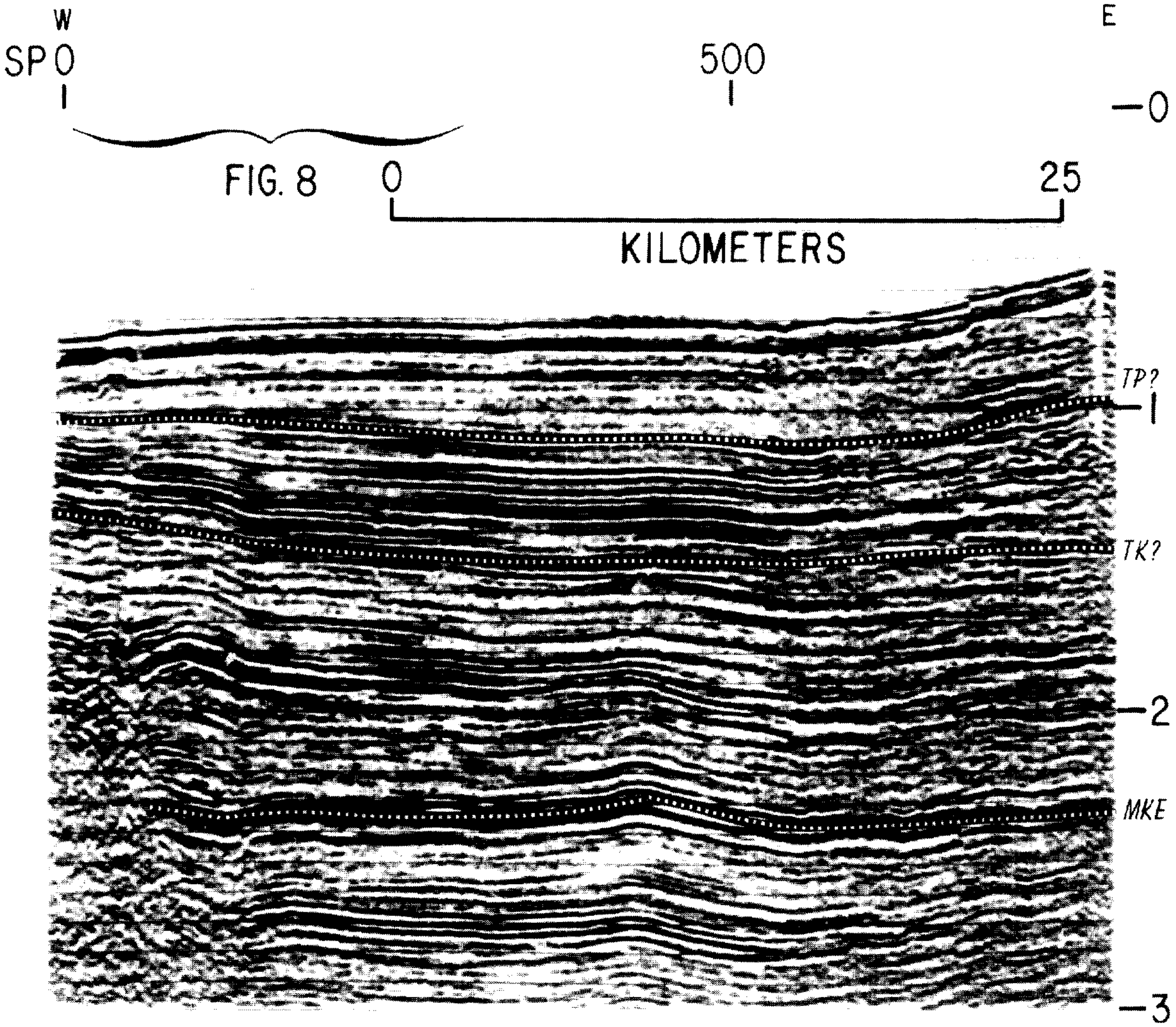

Figure 7—Squeezed section of line 5 showing coherent character of reflections from basinal carbonate section in Santaren Channel. Figure 8 details zone of dip changes and terminations near west end of this line.

of discontinuous reflections that extend to about 1.8 sec. Below 1.8 sec, the section generally lacks coherent reflections. A platform edge is visible beneath SP 2500 (Figure 5) at the extreme southern end of line 1.

Another salient feature of the anticlinal structure is its asymmetry. The north flank's maximum relief is about 1 km, and that of the south flank is about 500 m. The multichannel line reveals a prominent amplitude anomaly in the package of reflections that thins dramatically over the structural crest (Figure 9). This section thins threefold over the structure. The thinned section whitens out completely on the crest with some abrupt terminations of reflections as they reach the whitened zone.

A highly reflective contrast occurs beneath the whitened zone. The upper section is unconformable on the lower, as evidenced by packages of reflections that onlap on this surface on both flanks of the structure (Figure 9). A ramplike configuration of reflections at 1.7 sec between SP 1800 and 1950 (Figure 9A) may represent material that has been removed from the crest of the structure and redeposited off its north flank. The reflection character of the material below the unconformity is coherent and analogous to the inferred basinal carbonate material north of the structure. A deeper unconformity is present on the south flank of the structure where a zone of irregular but coherent reflections overlies a rough upper surface of a zone lacking coherent reflections. We infer this contact to record an upper zone of possibly tectonized basinal carbonate overlying shallow-water carbonate-platform material.

The correlation of the MKE within the basinal sequence to TLK at the contact between irregular coherent reflections and inferred platform carbonate rocks indicates the following approximate time-stratigraphic assignments for the reflection sequences. The shallow reflection interval above the whitened zone on the crest of the structure (Figure 9) has an interval velocity of about 2 km/sec and is inferred to contain Cenozoic deposits. The uppermost 0.2 sec of weakly reflective material, on the crest of the structure, is inferred to be mostly Neogene. The package of strong, coherent reflections just above the whitened zone on the crest of the

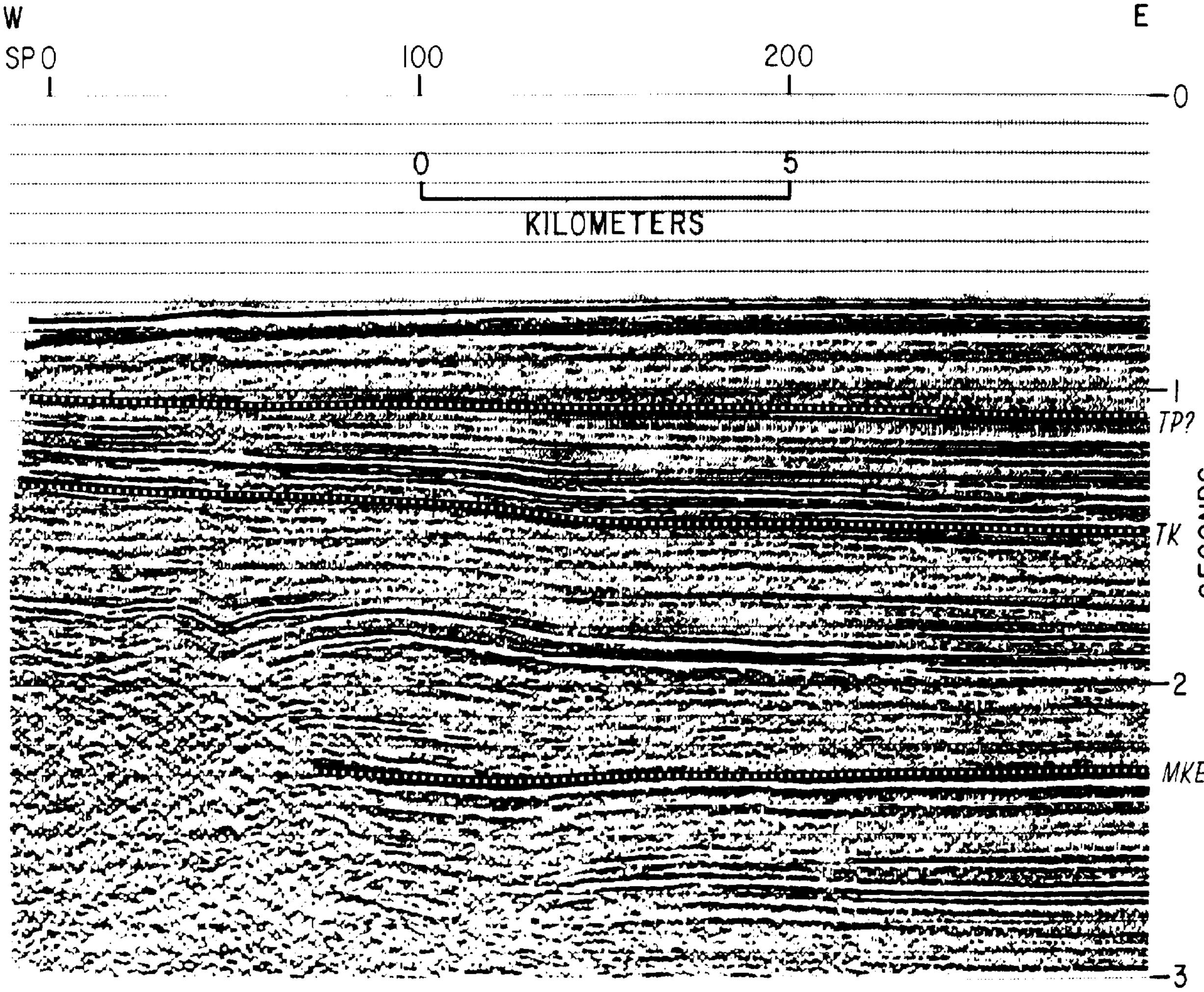

Figure 8—Time section of west end of line 5 showing deep, abrupt contact of seismic unit lacking internal reflections, with coherent reflections of basinal carbonates in Santaren Channel. Terminations and dip changes indicate that contact is locus of high-angle fault extending upward to 1.4 sec near top of inferred Cretaceous section.

structure thins from 0.3 to 0.15 sec between the north flank and the crest of the structure. Terminations of events occur in convergences suggestive of pinch-outs on unconformable surfaces. This reflection character may represent erosional activity in the basin facies during the Paleogene or early Neogene. The whitened zone may represent Upper Cretaceous chalk. The interval of continuous reflections below the whitened zone has interval velocities ranging between 3 and 4 km/sec. We interpret this reflection package to represent impedance contrasts in Upper Cretaceous rocks. The contact at the base of this interval appears to correlate approximately with the MKE in Santaren Channel toward the north and with the contact at the top of inferred carbonate-platform rocks on the south. A few deep reflections extend from the north beneath the anticlinal structure. In particular, the reflection at 3.1 sec is strong, coherent, and not readily explained as a multiple. The depth at 3.1 sec is approximately 6 km. The interval velocity between this event and the base of the supposed Upper Cretaceous section is 5.8 km/sec. Toward the south, the section within this interval—where reflections are lacking—is probably Lower Cretaceous in age and perhaps contains even older platform carbonate rocks. Toward the north, impedance contrasts in Lower Cretaceous and older basinal carbonate sediments are the probable source of plentiful coherent reflections. The apparent positive relief on deep events coming from the basin to positions beneath the structure may be an artifact of overlying, higher velocity materials.

No thinning on structure is apparent in the Lower Cretaceous and older sequences. The Upper Cretaceous reflection package thins regionally from north to south across the structure. There is no localized thinning on the structural crest within the Upper Cretaceous unit. Maximum loss of section is off the structure's south flank where the inferred uppermost Cretaceous and lower Cenozoic section thins by a factor of four. Upper Cenozoic sequences are twice as thick on the north flank and 20-30% thicker on the south flank than they are over the structure's crest. These thinning relationships indicate that the structure was initiated during the Late Cretaceous and that maximum topographic relief

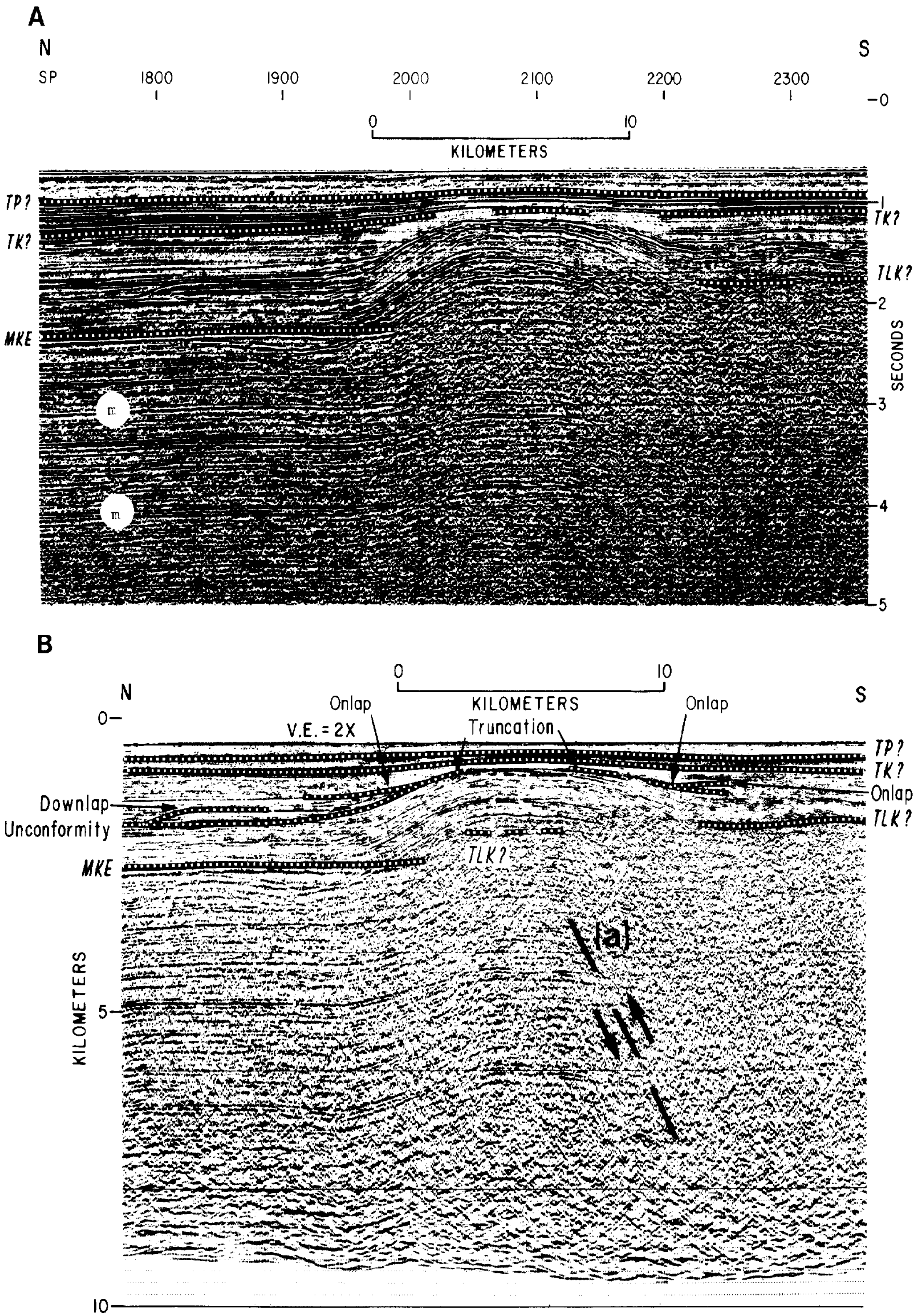
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Figure 9—(A) Time section of southern end of line 1 near confluence of Santaren, Nicholas, and Old Bahama Channels showing transition from inferred basinal carbonate strata to essentially reflectionless carbonate-platform material of inferred Early Cretaceous age. Broad anticline between SP 2000 and 2200 occurs above this contact. North flank of structure has relief of about 1.0 km; relief of south flank is about 500 m. Surface of zone with no reflections south of structure is at 1.8 sec. This surface is rough and probably represents karstified unconformity on Lower Cretaceous platform rocks (TLK). Upper Cretaceous basinal carbonate rocks characterized by continuous reflections are arched over the structure. Surface of this sequence is also an unconformity; reflection truncation is apparent between SP 2150 and 2200. Maximum thinning over structure occurs in zone of poor reflections overlying unconformity. This zone is inferred to be chalk of Late Cretaceous and early Cenozoic age. Band of strong reflections capping chalks indicates lithologic contrasts associated with unconformities in basinal carbonate section of largely Paleogene age. Capping zone of poor reflections is probably Neogene basinal carbonate sediment. Events marked (m) are probable short-path multiples following primary reflections by water-column time interval. (B) Migrated depth section of profile shown in A at vertical exaggeration of 2×, shows continuity of deep basinal reflections beneath anticline overlying basin to platform transition.

occurred in the early Cenozoic. Late Cenozoic expression of the structure could be a result of differential compaction of thick, semiconsolidated sediments on the structure's flanks.

The crossover of the MKE and the basal reflection of the inferred Upper Cretaceous sequence implies that some energy is arriving from out of the plane of the section. Based on the location of the Idris (1975) crossing and the observed northwest dip on the extreme southeast end of line 4 (Figure 1), the western part of the structure appears to trend only slightly south of west at an angle nearly perpendicular to line 1.

NICHOLAS CHANNEL

A major structure (Figures 10, 11) occurs at the eastern end of line 2 between SP 100 and 500. This feature has a steep eastern flank that has a relief of about 1 km and a flank breadth of 4 km (Figure 11). Coherent reflections from inferred basinal carbonate sediments abut the margin of the structure, which has few well-defined reflections and is probably composed of shallow-water carbonate-platform material.

In the basinal section adjacent to the structure's eastern flank (Figure 11), terminations and changes in dip indicate small normal faults with down-to-the-east throws of tens of meters. Diffractions and dip reversal at the base of this basinal section at 1.5 sec indicate that the eastern flank may be faulted. Faults appear to die out in the middle to late Cenozoic section, and the more or less structureless late Neogene sequence blankets the older basinal section. Between SP 0 and 100, in the basin facies, low-relief anticlines below 1.6 sec may represent incipient salt pillows uplifted over evaporitic material displaced from beneath the inferred platform carbonate.

The basinal sediments on the 40-km long, sloping western flank of the structure onlap the platform material from a depth of 1 km to the crest, which is only 300 m subbottom. The surface of the inferred shallow-water platform block is rough: protuberances are over 100 m high with apparent widths of about 1 km (arrows in Figure 11). These features are suggestive of the karst hills known as mogotes that have developed on carbonate terranes at various places in the Greater Antilles. From the track chart of Idris (1975), it is clear that the second structure Idris encountered on a north-northwest–south-southeast crossing is present on the eastern end of line 2 on an east-west crossing. The steeper flank shown in the Idris (1975) data dipped north. Therefore, true dip of the steep flank is toward the northeast. A graben at SP 900 (arrow in Figure 10) offsets basinal sediments 100 m and appears to mark the block's western edge.

On the western end of line 2, a weakly reflective Neogene section is consistently shown at the top, overlying a sequence of high-amplitude, discontinuous reflections that mark seismic impedance contrasts in basinal Upper Cretaceous and lower to middle Cenozoic rocks (Figure 10). Channeling is apparent on the sea floor, and structures suggestive of buried channels and unconformable surfaces are present in these sediments.

A platform edge at the western end of line 3 (Figure 12) is more clearly depicted than on line 2. The top of the inferred Lower Cretaceous section peaks at 0.8 sec subbottom in a ridge whose basinward, western slope extends down to 3 sec. Reflective basinal section onlaps its western slope. We believe the ridge and slope mark the location of a Lower Cretaceous platform edge. The breadth of the ridge at the slope break is 2-3 km. The ridge has a relief of about 100 m over the back-reef or platform interior surface. The relief of the platform edge over the floor of the adjacent basin appears to be at least 1 km. The angle of declivity of the slope approaches 20°. The deepest coherent reflections in the basin sequence are at a depth of about 3,400 m, so the basinal section is about 2 km thick (Figure 12). Below 3 sec, west of this platform edge, material lacking coherent reflections may be an even older, more extensive, Cretaceous or Jurassic carbonate platform.

GRAVITY AND MAGNETIC MEASUREMENTS

The potential field data (Figure 13) acquired along our seismic lines are too sparse to map. They nevertheless supply important constraints to the interpretation of the seismic data. The magnetic anomalies are of long wavelength, and few paired positive-negative reversals occur on any of our lines, indicating that depth to magnetic basement is exceedingly great in Santaren and Nicholas Channels (Figure 1).

An 8-mgal positive edge effect occurs at the contact between basinal sediments of Santaren Channel and the inferred Lower Cretaceous shallow-water carbonate-platform rocks at the southern end of line 1 (Figures 5, 9). This anomaly is not localized on the anticlinal structure at SP 2000-2200. Instead, it appears to reflect the positive density contrast between the shallow-water carbonate-platform rocks and the lower density basinal sediments toward the north. A 12-mgal positive anomaly is associated with the tilted block of inferred platform carbonate

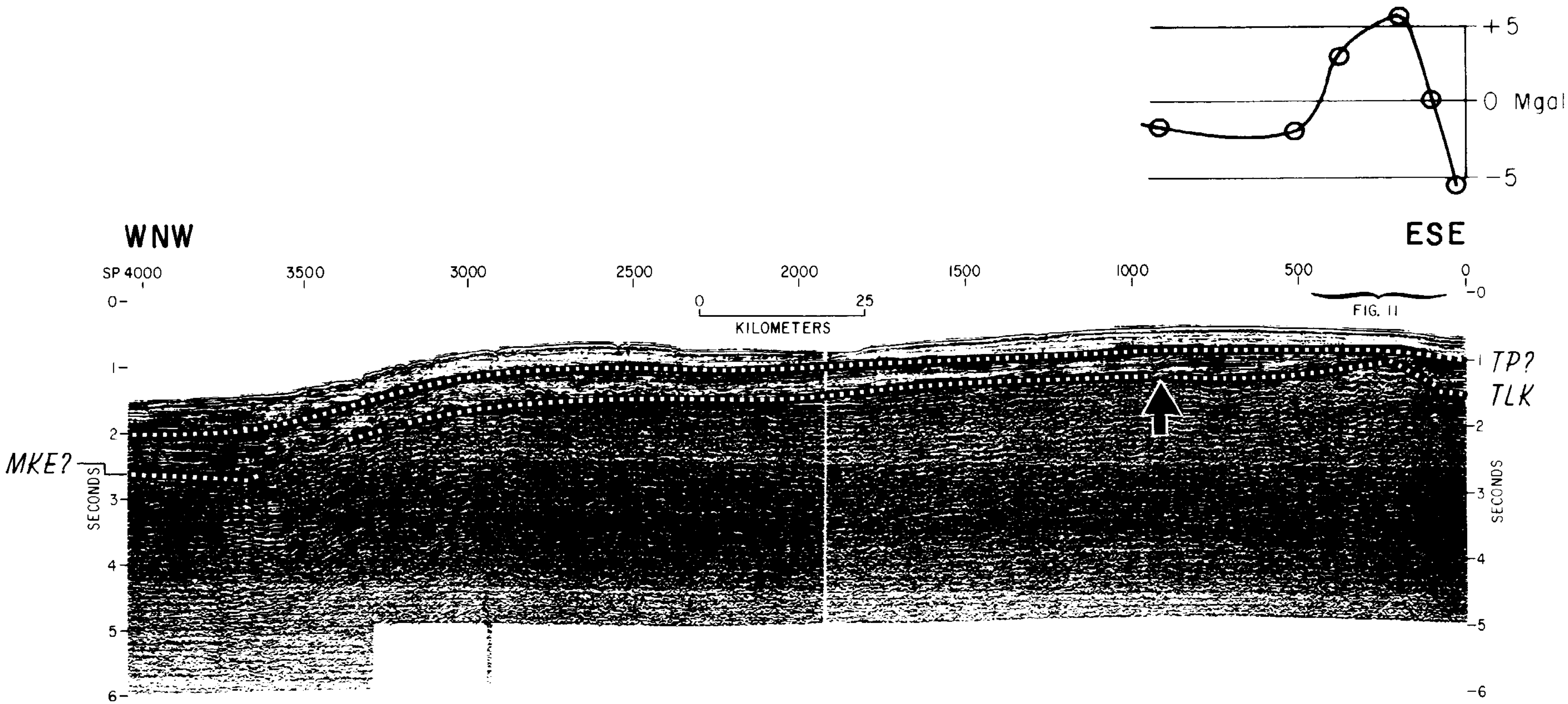

Figure 10—Squeezed seismic section of line 2 in Nicholas Channel extending for 200 km (Figure 1). Line reveals an Upper Cretaceous and Cenozoic section onlapping inferred Lower Cretaceous platform carbonates from west to east. An unconformity that occurs at surface of zone of incoherent reflections is thought to overlie Lower Cretaceous platform material. A large, buried fault-bounded block of platform material underlies eastern end of line. This structure is accompanied by positive free-air gravity anomaly shown in upper margin and has no attending magnetic anomalies. Arrow at SP 900 marks graben that occurs at western edge of tilted block. Western edge of platform lies beneath SP 3500.

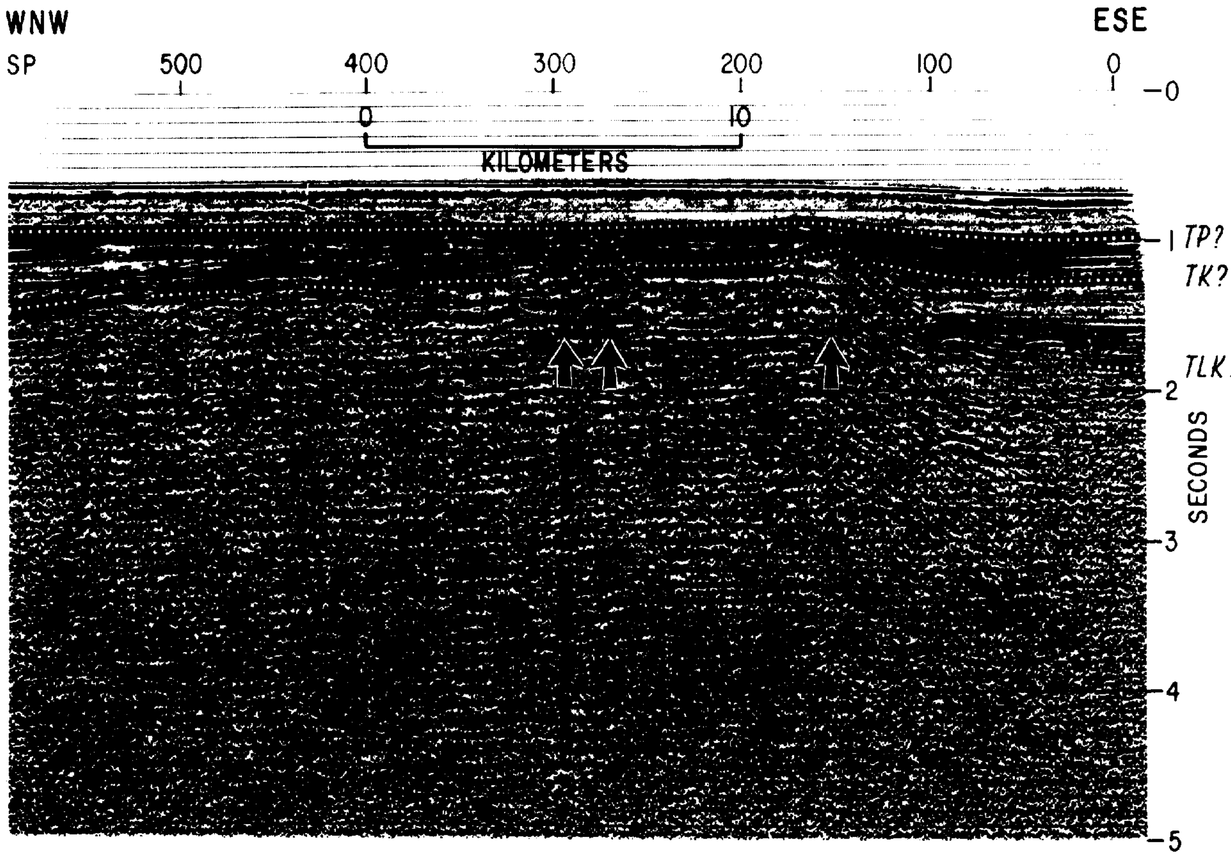

Figure 11—Time section of segment of Figure 10 showing block of shallow-water platform material, onlapped by younger Cretaceous and Paleogene basinal carbonates and capped by Neogene basinal carbonates at SP 300, at its shallowest depth beneath sea floor. This block is more than 40 km broad and has steep east slope with 1.0-km relief over horizontal distance of 3 km. Reflections terminating against this slope are marked by dip changes and obscured by diffractions; it follows that slope may be fault scarp. Surface of this platform block is rough with protuberances approximately 100 m high and 1.0 km across (marked by arrows). These dimensions are reminiscent of karst hills (mogotes) seen on limestone terrains onshore in Cuba and Puerto Rico.

material at the east end of line 2 (Figures 10, 11). Allowing for a 0.3-gm/cm^3 density contrast between the platform carbonates and the surrounding, less dense, basinal carbonate material accounts for the observed anomaly. Neither of these features has an associated magnetic anomaly, which suggests that dense platform carbonate comprises the core of both structures and that no igneous or metamorphic rocks are present at shallow depths in either feature.

DISCUSSION

Seismic Facies in Carbonate Rocks

Our observations reveal two seismic facies expressing the carbonate rocks of the southwestern Bahamas. The basinal facies, located in the topographic basins of Santaren and Nicholas Channels, typically produces continuous flat-lying reflections. This reflection character is thought to result from seismic impedance contrasts caused by interbedding of storm-derived allochthonous shallow-water carbonate material with sediment composed of tests of pelagic organisms that rain continuously on deep-water carbonate environments. Where the supply of rapidly derived, storm-supplied materials is limited, whitened zones lacking internal reflections occur as subfacies. This whitened subfacies is inferred to represent Late Cretaceous and Cenozoic chalk in Santaren and Nicholas Channels.

A second facies has a highly reflective rough surface bounding zones that lack good, continuous internal reflections. This facies is onlapped by basin facies on the margins of topographic basins and can be traced from beneath basin facies upslope into the present platform slopes of Cay Sal and the Great Bahama Banks. We have referred to this seismic facies as the platform facies in the region of the southwestern Bahamas. The platform facies is also characterized by a positive gravity anomaly and the lack of any associated magnetic anomaly. Platform facies appears beneath the basin facies in Nicholas Channel and at the south end of Santaren Channel.

Although the platform facies is relatively uniform in the southwestern Bahamas, this uniformity is not everywhere the case. Where carbonate platforms border continental landmasses, influx of terrigenous clastics commonly results in good reflections within the platform interior or lagoonal setting. We can envision bedded evaporites in the interior

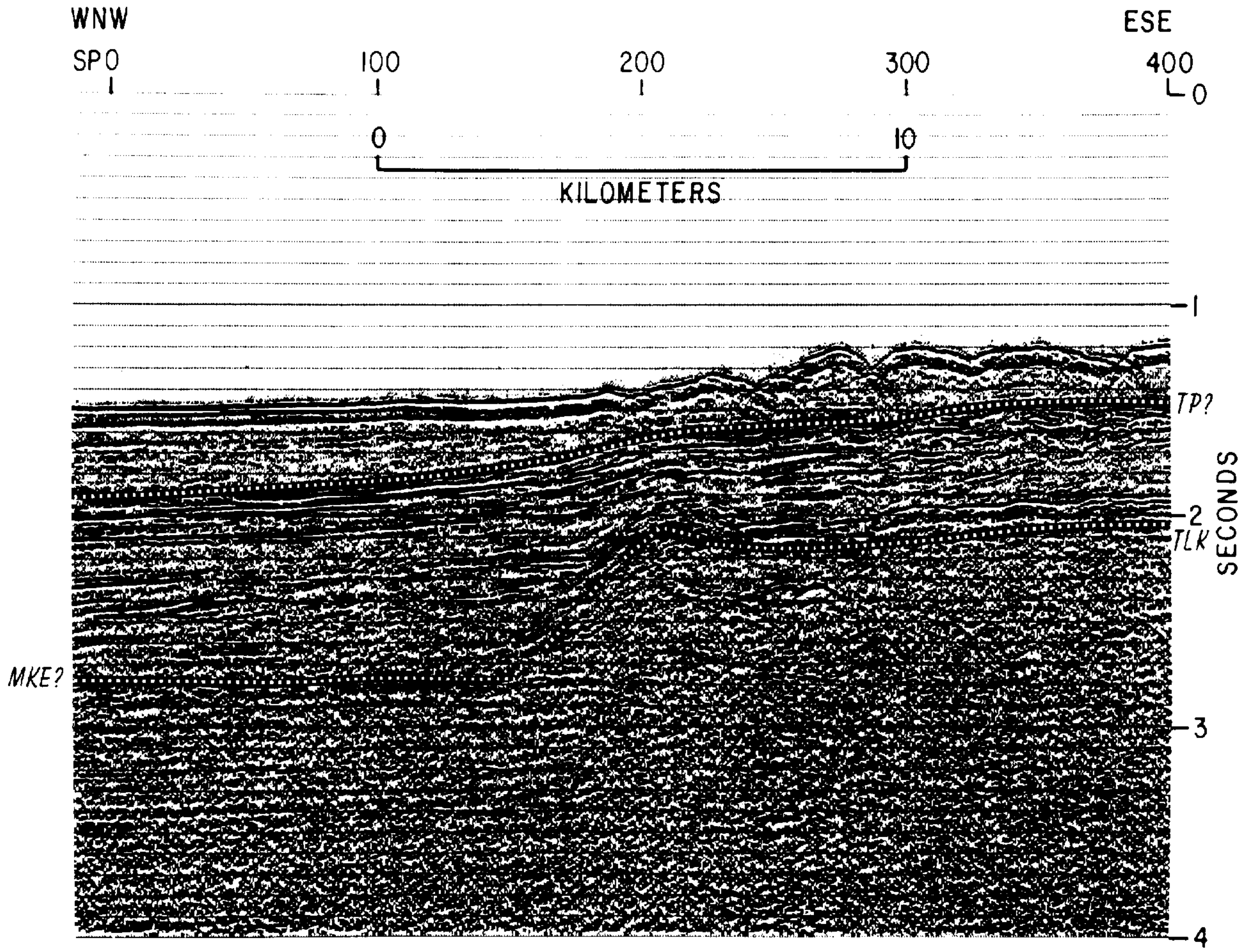

Figure 12—Time section of western end of line 3 showing configuration of platform edge beneath SP 200. Edge has relief of about 1.0 km across horizontal distance of about 4 km. Highest portion of this bank margin appears to be as much as 200 m above surface of platform interior toward east.

setting also giving rise to lithology contrasts that would result in continuous internal reflections.

The general rules would seem to be that elevated platform edges or "reefs" most typically lack good internal reflections, but such reflections may appear in lagoons or platform interiors. Internal reflections are typically present in carbonate basin facies; where they are lacking in basins, chalk intervals may be presumed.

The lack of reflections in elevated platform rims is in part a result of their upward convexity, which tends to dissipate reflected seismic energy. More importantly, the positive relief of the platform edge exposes these features to prolonged episodes of freshwater diagenesis and karstification (Popenoe et al, 1984). The entire surface of platform materials seen in our records indicates karstification, which may explain the general lack of internal reflections in the inferred shallow-water carbonate-platform setting in the vicinity of Santaren and Nicholas Channels.

Anticlinal Structure

The anticlinal structure located between SP 2000 and 2200 on line 1 (Figures 5, 9) occurs at the northern edge of Bahaman carbonate masses that were involved in the Cuban collision. A transition from a topographic basin on the north to a shallow-water platform in the south occurs beneath the anticline. The asymmetric folding of strata above the transition is best explained as a result of compressional tectonism.

Numerous anomalous variations in thickness in the largely Upper Cretaceous section are bowed up in the anticline. These strata thin from 1.5 km on the north, in Santaren Channel, to 1.1 km on the structural crest (Figure 9). Truncations indicate that some of this thinning results from erosion on the structural crest. The most dramatic thinning is on the southern flank of the structure, where upper units converge abruptly (at SP 2200) to a vertical dimension of only 600 m. Significant dip changes do occur on the south flank, but no other clear-cut indications of faulting are found at this point. Deep terminations occur, below 4 km depth, in inferred basinal sediments beneath the anticline, 3 km north of the zone of dip and thickness variation. Some major dislocation related to faults may have caused the aberrant dips and local thickness variations. However, the regional thinning was caused by southward onlap of basinal

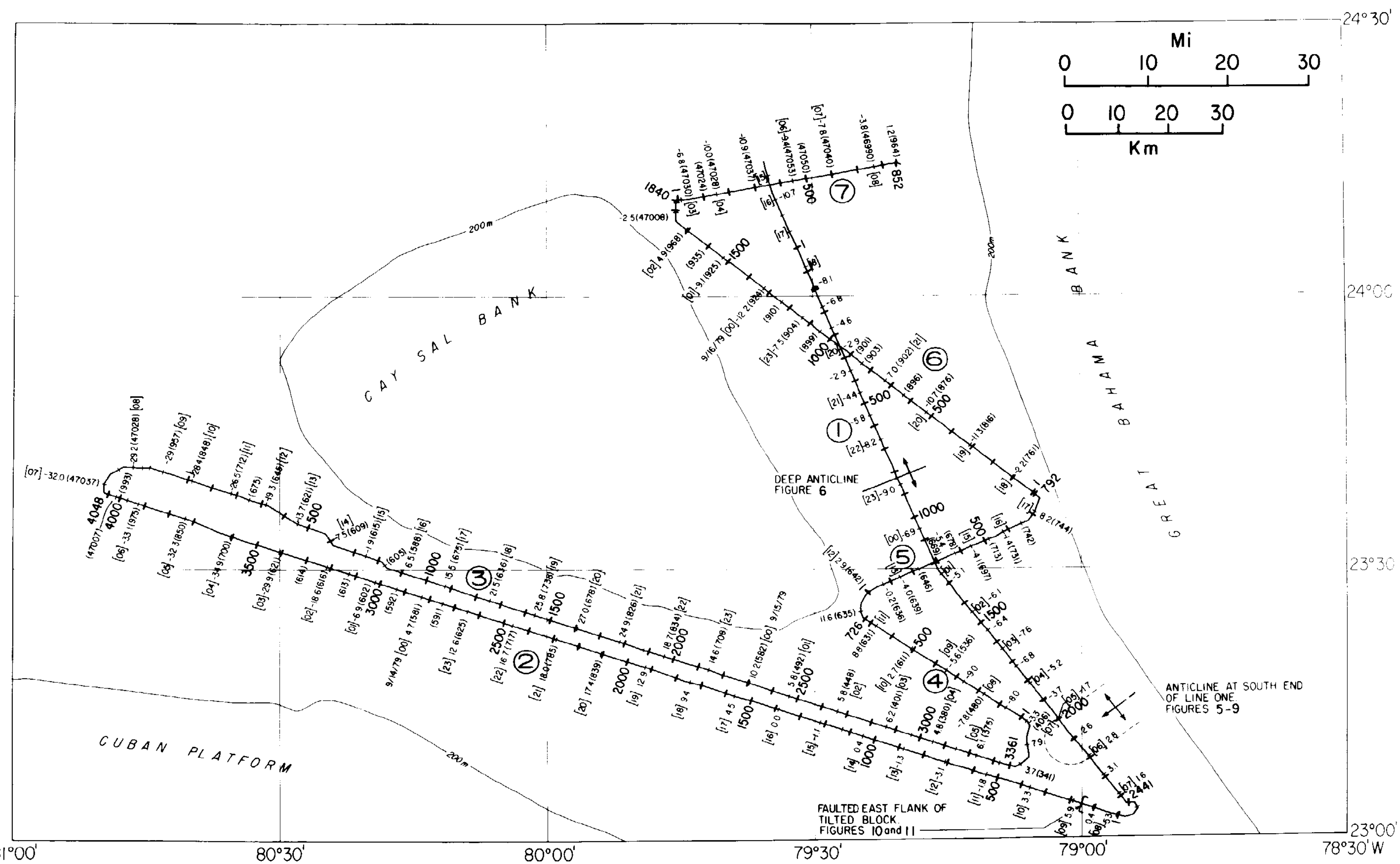

Figure 13—Potential field data shown with time and shot-point numbers along track lines. Circled figures are line numbers. Numbers in 500-unit intervals are shot points. Small numbers in brackets are times in hours. Numbers with one decimal place are free-air gravity anomalies computed using gravity formula for Geodetic Reference System, 1967 (Woollard, 1979). Numbers in parentheses are total field magnetic anomalies. Only last 3 digits are shown for 46,000 gamma values. Where values rise above 47,000, all 5 digits are shown.

carbonates on shallow-water carbonate material. Subsequent compressional tectonism produced the anticline.

What is most clear is that the northern edge of the Bahaman carbonates disrupted by Cuban tectonism does not look like a typical arc-trench system where an arc overrides relatively incompetent oceanic crust. In reflection records, this family of plate boundaries reveals some indication of a subducting plate overlain by a melange of sediment containing counterregional dipping reflections interpreted to represent thrust-fault planes (for examples see Hamilton, 1977). Our crossing of the northern edge of the Bahaman-Cuban collision zone appears more like the asymmetric anticlinal features seen in some dip sections across the leading edges of Cordilleran thrust belts, where competent basement blocks shove overlying sedimentary rocks into anticlinal configurations (Harding and Lowell, 1979, their Figure 7). If this analogy is meaningful, we must postulate that the thick platform carbonates of the Bahamas behave in a competent manner more analogous to continental basement. Both the great sediment thickness and the high interval and refraction velocities, noted at relatively shallow depths in Santaren Channel, are consistent with this speculation. However, this does not rule out the possibility that the area may overlie crust of originally oceanic composition.

As a first approximation, we believe that the structure visible at the south end of Santaren Channel is a hanging-wall anticline at the northernmost edge of the Cuban fold-thrust belt (Figure 9B). This conclusion is consistent with our observation that reflections from the basinal section on the north appear to continue for some distance beneath the inferred platform carbonates toward the south. It is also consistent with what we envision as the tectonic setting of this structure. Hanging-wall anticlines or compressional blocks as they are referred to by some authors (Harding and Lowell, 1979) are typically located at the outer edge of fold-thrust belts. Because of their relative simplicity, these structures are deemed by many to be the most attractive within the fold-thrust regime for trapping oil and gas (Harding and Lowell, 1979). If our speculations are correct, similar features could occur for many tens of kilometers to the southeast off Cuba's Camagüey province (Figure 2A).

The timing and sequence of events deduced from onshore geology in Cuba fit with observations from our data. If our pick of the MKE and its approximate correlation with the top of Early Cretaceous shallow-water platform carbonate rocks are correct, then the anticlinal structure appears to have been formed in the Late Cretaceous and early Cenozoic. The major unconformity, indicated by truncation of reflections in the crest of the structure and by pinch-outs of onlapping reflections on its flanks, appears to have occurred during the Late Cretaceous. Discordances and conglomerates are abundant in onshore well and outcrop data at the Cretaceous-Cenozoic boundary (Meyerhoff and Hatten, 1968; Pardo, 1975). The rough nature of the inferred top of Lower Cretaceous platform rocks and the marked change in reflection character across this contact indicate that this surface is a major unconformity. The unconformable nature of the upper surfaces of both Lower and Upper Cretaceous sections is also evidenced by marked increases in interval velocity across both events.

Tilted Block

The tilted block of inferred shallow-water carbonate-platform rock (Figures 10, 11) is presumably related to tectonism in the Cuban collision zone. The upper surface of the block is clearly eroded and onlapped by Upper Cretaceous and Cenozoic basinal carbonate sediments. The history of movement of this block differs from that of the anticlinal feature at the south end of line 1. The major difference appears to be that the basinal section did not onlap the block prior to its uplift because the block lacks any upward-arched Late Cretaceous basinal material over its crest. The occurrence of a well-defined, positive gravity anomaly over the block argues that its origin is not related to upward arching over a salt pillow; instead, it favors uplift resulting from compressional tectonism.

The inferred basinal section above TLK, which onlapped the carbonate block after its uplift, lacks coherence compared to the basinal section in Santaren Channel to the north. Differential compaction over the rough surface of the underlying platform carbonates in Nicholas Channel may explain to some degree the incoherent character of overlying reflections (Figure 10). The rough surface of the underlying platform rocks may be related to faulting that is undetectable in the platform materials, owing to a lack of internal reflections.

Lower Cretaceous Reef Trend

Depositional structure related to the occurrence of reefs or platform edge-slope complexes within the Cuban-Bahaman contact zone are clearly identifiable in the western reaches of Nicholas Channel (Figure 12). The platform edge, visible at SP 200 in Figure 12, appears to have a western slope relief that exceeds 1 km. The crest of the edge occurs at 2 sec, is 2 km broad, and has a positive relief of 100 m over the platform interior to the east. A similar, though smaller, platform edge occurs at SP 2500 on line 1 (Figure 5). Other platform edges seen in our seismic profiles have morphologies that are modified by tectonism and erosion.

The Lower Cretaceous platform edge at SP 200 (Figure 12) must embay some distance toward the north in the Straits of Florida. North of Cay Sal Bank, a deep-basin arm must branch off the straits toward the southeast in Santaren Channel (Figure 14). Schlager et al (in press) documented the occurrence of a similar Early Cretaceous deep-water embayment in the eastern Bahamas.

Sheridan et al (1981) believed the Straits of Florida developed in the Late Cretaceous and that prior to its existence a broad shallow-water platform extended continuously from Florida through the Bahamas. However, our data show that Early Cretaceous basinal deposits existed in the region of the straits. It follows that the southern Florida Strait was in existence during the Early Cretaceous and that segmentation of the Bahaman shallow platform by deep-water channels predated the Late Cretaceous.

Earlier interpretations of the distribution of this platform edge, based on less information, carried the Lower Cretaceous reef southeastward from the last known occurrence on the southern slope of the Florida peninsula to the outcrop area of northern Cuba (Figure 14). Our data suggest a more complicated picture. Indeed, using the isolated plat-

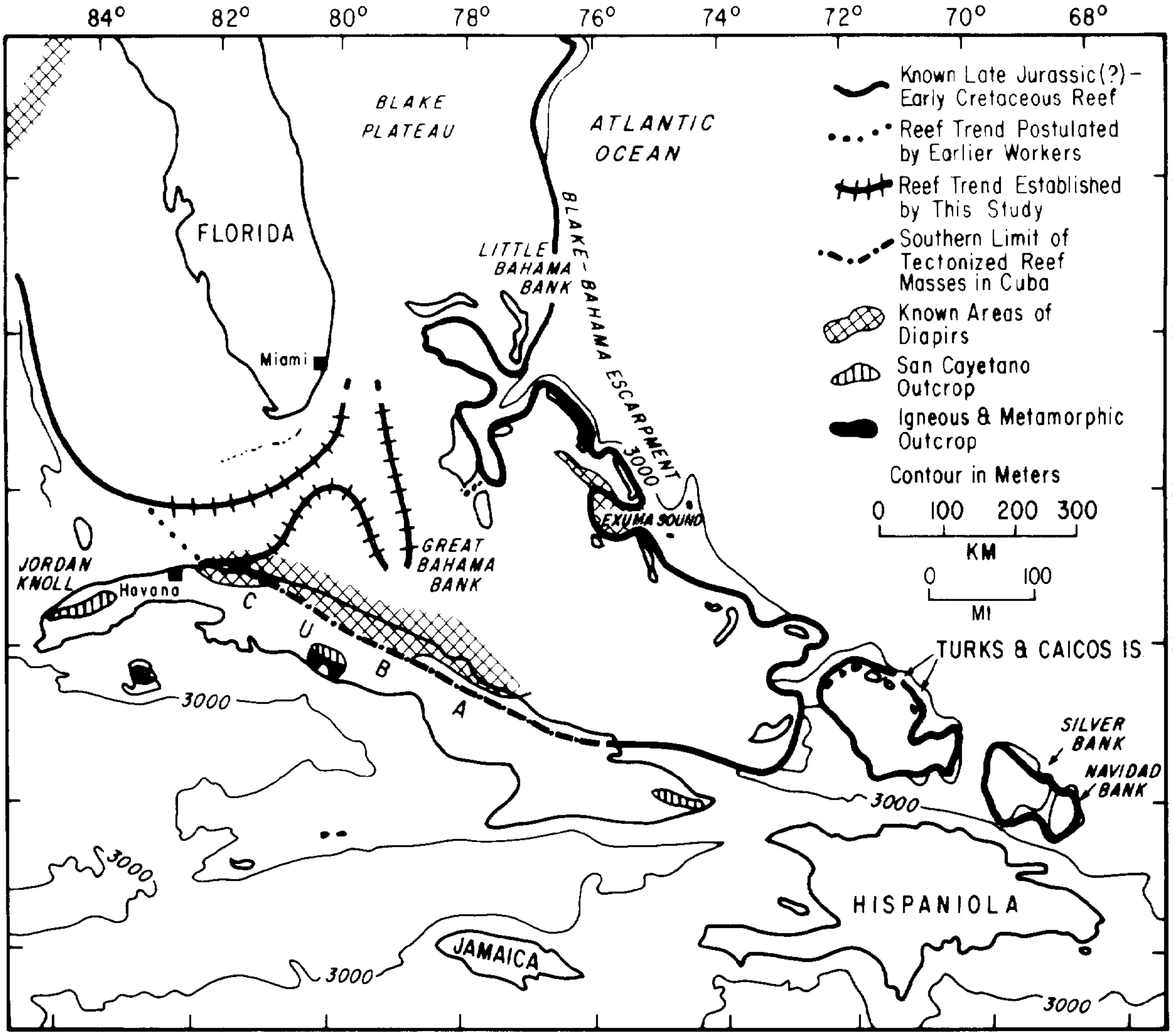

Figure 14—Inferred Lower Cretaceous reef trends (after Meyerhoff and Hatten, 1974, their Figure 5). Northward extension into Straits of Florida and Santaren Channel indicates more complicated platform-edge distribution than had been formerly believed. This change is necessitated by new information presented in this report.

form masses of the southeastern Bahamas as a model and considering the occurrence of both basinal and platform carbonates in northern Cuba, it seems likely that distribution of Lower Cretaceous platform edges in this region could well be complicated to a degree that defies complete reconstruction.

CONCLUSIONS

Seismic reflection measurements at the northern edge of the Bahaman-Cuban collision zone, in the southwestern Bahamas, reveal two seismic facies. In Santaren Channel, east of Cay Sal and west of the Great Bahama Bank, a 5-sec sequence of coherent and generally undisturbed reflections is inferred to represent an accumulation of deep-water carbonate sediments approximately 10 km thick. At the south end of Santaren Channel and in Nicholas Channel, separating Cay Sal and Cuba, the deep-water carbonates terminate against and onlap zones generally lacking coherent reflections. The incoherent zones are inferred to be shallow-water, carbonate-platform rocks, and they coincide with positive gravity anomalies. A positive density contrast, due perhaps to some dolomitization and the presence of anhydrites in the platform carbonate facies, is consistent with this inference. Neither seismic facies has attendant short wavelength magnetic anomalies.

Age assignments are primarily based on a jump correlation with seismic data to the north that have been tied to the GE-1 well east of Jacksonville, Florida. In Santaren Channel, a strong seismic event at 2.3 sec appears to correlate with a mid-Cretaceous event identified to the north. This relationship, together with consideration of interval velocities and the common occurrence of a whitened zone that is correlated with Late Cretaceous chalks, completes the rationale for our age assignments.

An asymmetric anticlinal structure, with an apparent width of 10 km, occurs at the southern end of Santaren Channel at the transition between basinal carbonates on the north and shallow-water platform carbonates on the south

(Figure 9). The north flank of the anticline has a relief of at least 1 km; the southern flank's relief is about 500 m. The MKE within the basin facies appears to correlate with the rough upper surface of platform carbonates beneath the anticline. This indicates that the platform carbonates within the anticline's core are at least Early Cretaceous in age and are bounded by an overlying unconformity. Late Cretaceous and Paleogene sequences thin fourfold on the structure. Upper Cretaceous basinal sediments seem to have onlapped shallow-water platform material that was subsequently uplifted during the Late Cretaceous. Truncation of strata on the crest of the anticline and sediment fills on the structure's flanks mark a major unconformity near the Cretaceous-Cenozoic boundary. Basinal events older than mid-Cretaceous can be traced southward beneath the anticline for about 10 km. We speculate that this structure is a hanging-wall anticline marking the northern limit of thrusting in the Cuban arc. Our age inferences for evolution of this feature are consistent with those established for thrusting onshore in Cuba. Because the anticline's dimensions are large and intriguing amplitude anomalies occur on its crest, it seems a likely target for oil and gas exploration.

A 40-km broad, tilted fault block in eastern Nicholas Channel is inferred to be composed of shallow-water platform carbonates because it generally lacks coherent internal reflections, is attended by a positive gravity anomaly, and has no associated short wavelength magnetic anomalies. The faulted eastern face of this structure has a relief of more than 1 km and an apparent dip of 20°. The crest is buried beneath 300 m of Neogene sediment. The western slope of the block extends for 40 km and is terminated in a graben that offsets platform carbonates by 100 m. The fault block is onlapped by sediments inferred to be Late Cretaceous and Cenozoic in age. It appears that the block was uplifted prior to latest Cretaceous time. The continuation of fault activity into overlying Neogene sediments may have resulted from differential compaction or relaxation of compressional stresses with attending isostatic adjustments.

Our records reveal a buried carbonate-platform edge in the western extremity of Nicholas Channel, at its junction with the southern Straits of Florida. Based on our correlations, the age of this feature is Early Cretaceous. From this correlation, it appears that a Lower Cretaceous platform edge must bound Cay Sal Bank on both its northwest margin, against the Straits of Florida, and its northeast margin, bordering Santaren Channel. The platform to basin contact seen at the south end of Santaren Channel is faulted.

Bahaman crustal elements behaved in a competent manner more akin to that of basement rocks in continental thrust zones than to oceanic crustal elements in arc-trench systems. However, the thick Bahaman carbonates in this region may overlie a crust with an original oceanic composition.

Our observations are consistent with previous work, which indicates that the history of the Bahaman-Cuban collision in a paleo-plate boundary zone includes compressional tectonism whereby major units of the Bahamas collided with the Cuban arc to cause thrusting and faulting. Salt tectonism may have further complicated the dynamics of this unique region.

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