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Bolide impact effects on the West Florida Platform, Gulf of Mexico: End Cretaceous and late Eocene

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ABSTRACT

This study documents seismic reflection evidence that two different bolide impacts significantly disrupted stratigraphic and depositional processes on the West Florida Platform (Gulf of Mexico). The first impact terminated the Late Cretaceous Epoch (Chicxulub impact, Mexico; ca. 66 Ma; end-Maastrichtian age). The second took place in the late Eocene (Chesapeake Bay impact, Virginia, USA, portion of the Chesapeake Bay; ca. 35 Ma; Priabonian age). Both impacts produced far-reaching seismic shaking and ground roll followed by an impact-generated tsunami, the effects of which are evident in the seismostratigraphic record. The Chicxulub seismic shaking caused collapse and shoreward retreat of the Florida Escarpment and widely disrupted (faulting, folding, slumping) normal flat-lying shelf beds. The associated tsunami currents redistributed these shelf deposits and mixed them together with collapse debris from the escarpment to form a thick wedge of sediments along the base of the escarpment. The Chesapeake Bay impact created a mounded sedimentary deposit near the outer edge of the late Eocene ramp slope. This deposit also has a bipartite origin. A lower layer is marked by an echelon faulting created in situ by seismic shaking, whereas an upper layer represents sediments redistributed from the late Eocene shelf and upper ramp slope by tsunami-driven bottom currents (debris flows, contour currents, slumps). This is the first report of seismic effects from the Chesapeake Bay impact in the Gulf of Mexico. These results further demonstrate that large-scale marine bolide impacts have widespread effects on the stratigraphic and depositional record of Earth.

INTRODUCTION

The West Florida Platform constitutes the western half of the Florida Platform, a large sedimentary edifice (dominantly Mesozoic and Cenozoic carbonates) that separates the eastern Gulf of Mexico from the western North Atlantic Ocean (Fig. 1). The study area extends ~700 km from DeSoto Canyon in the northwest to the Straits of Florida in the southeast and averages ~300 km in width from the Florida Escarpment to the Florida shoreline; total area is ~200,000 km² (Fig. 2). The general stratigraphic framework of the West

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Florida Platform is well known (Salvador, 1991a; Randazzo, 1997; Snedden and Galloway, 2019), and several detailed studies focused on limited geographic areas and/or stratigraphic intervals (e.g., Dobson, 1990; Dobson and Buffler, 1997; Jee, 1993). Seismic reflection data analyzed in this study indicate that two unusual disruptions of normal depositional processes on the West Florida Platform can be correlated with bolide impacts: one at the end of the Cretaceous Period (Chicxulub event, impact location in Mexico); the other during the late Eocene Epoch (Chesapeake Bay event, impact location beneath Virginia, USA, portion of the Chesapeake Bay).

METHODS AND MATERIALS

For this investigation, I analyzed migrated, two-dimensional, multichannel seismic reflection data from seven different survey programs, which are publicly available online from the U.S. National Archive of Marine Seismic Surveys (<https://walrus.wr.usgs.gov/NAMSS>; Fig. 3; Table 1). Because different companies collected the seismic data in different years (1974–1988) using different surveying and processing systems, seismic resolution varies among the data sets. In order to provide more detailed interpretations and illustrate them more clearly for the reader, I have compressed the seismic reflection lines horizontally and stretched them vertically, which exaggerates the architecture of the features (vertical exaggeration roughly 11:1–17:1 at the seafloor). A total of 327 lines yielded 40,405 line km of data (Table 1). In addition, I acquired biostratigraphic data—mainly last occurrences of key planktonic foraminifera and calcareous nannofossils—from 28 petroleum-industry boreholes. Twenty-four are located in federal waters and four in state waters (Fig. 3; Table 2). Borehole data from federal waters may be obtained online from the U.S. Bureau of Ocean Energy Management (<https://boem.gov>). I personally analyzed foraminifera and ostracoda from the Texaco 2523-1 borehole but relied on public data (both published and unpublished) for the remaining boreholes. All stratigraphic levels identified in industry boreholes are approximate because samples were taken at meter-scale intervals and all samples were cuttings, not cores. Several shallow coreholes (Mitchum, 1978; Mullins et al., 1988a) and seafloor dredges (Freeman-Lynde, 1983; Mullins et al., 1988b; Paull et al., 1990) as well as four short shelf-edge seismic lines (Corso et al., 1988) provided additional data from the outer platform slope and escarpment face (Fig. 4).

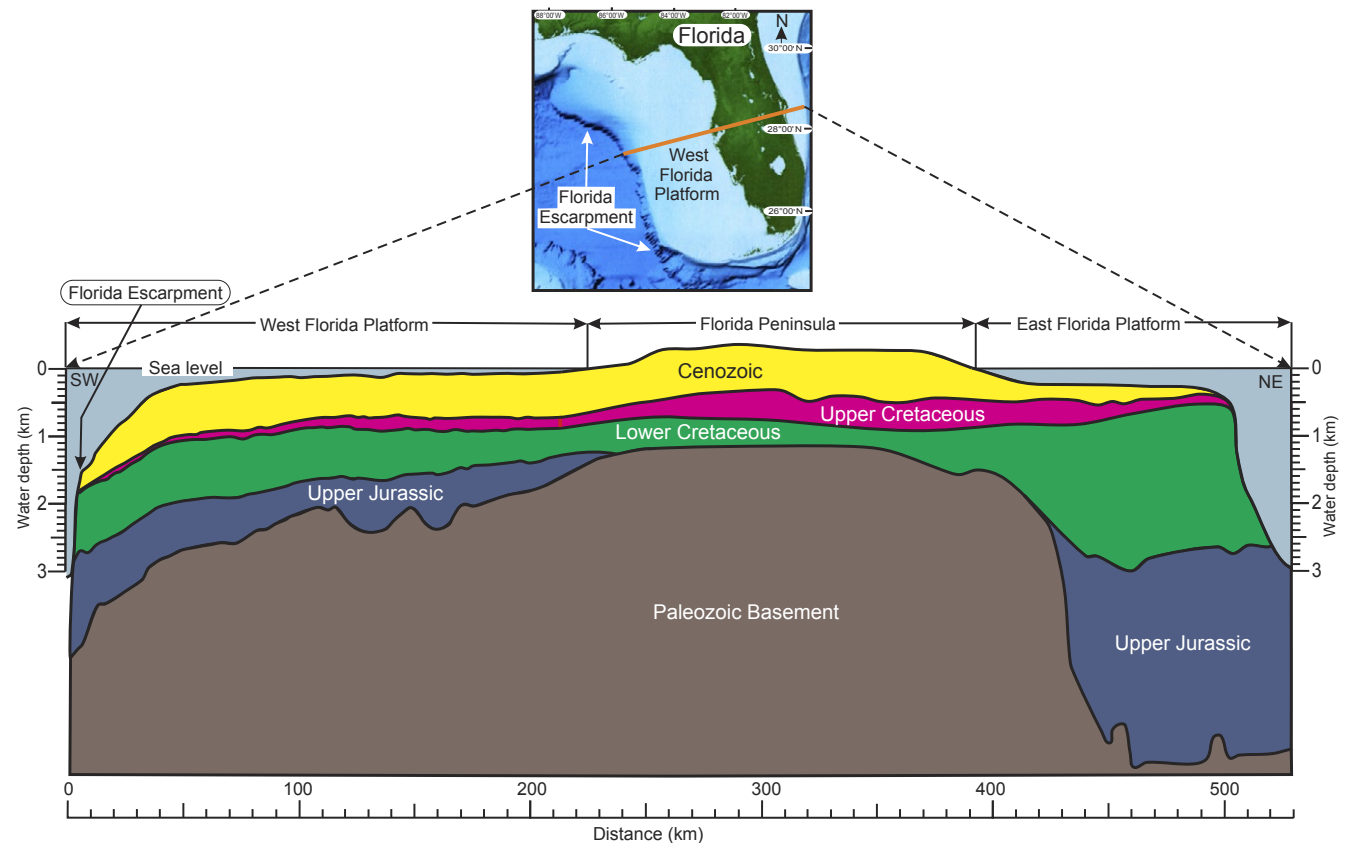


Figure 1. Schematic cross section of the Florida Platform (Gulf of Mexico), approximately transecting the middle of the platform. Modified from Randazzo (1997).

PREVIOUS INVESTIGATIONS

Early seismic profiling using the arc method, along with seismic refraction and reflection studies in the 1960s, established the general physiography, structure, and stratigraphic succession of the northwestern half of the West Florida Platform (Antoine and Harding, 1965; Antoine and Jones, 1967; Antoine et al., 1967; Uchupi and Emery, 1968; Bryant et al., 1969). These studies along with at least one piston core from the escarpment documented presence of a linear shallow-water carbonate buildup ("reef") along the Early Cretaceous platform edge. Mitchum (1978) used seismostratigraphic sequence analysis (sparker and shallow borehole data) to document a major shift on the outer West Florida Platform from shallow-water shelf deposition in the Early Cretaceous to

deep-water slope conditions in the Cenozoic. Ball et al. (1988) published the earliest analysis of a comprehensive grid of multifold seismic reflection lines (1770 line km) tied to 17 deep industry boreholes and interpreted basement structures and general stratigraphy of the northwestern and central parts of the West Florida Platform. Salvador (1991a) published a geological synthesis of the entire Gulf of Mexico basin. Summary chapters in this compendium included specific stratigraphic intervals on the West Florida Platform: Triassic-Jurassic (Salvador, 1991b); Lower Cretaceous (McFarlan and Mendes, 1991); Upper Cretaceous (Sohl et al., 1991); and Cenozoic (Galloway et al., 1991). Snedden and Galloway (2019) published the most recent basin-wide analysis of depositional and paleogeographic history, updating earlier interpretations with abundant new seismic and borehole data. Three of their schematic dip lines cross the Florida Escarpment and adjacent West Florida Platform.

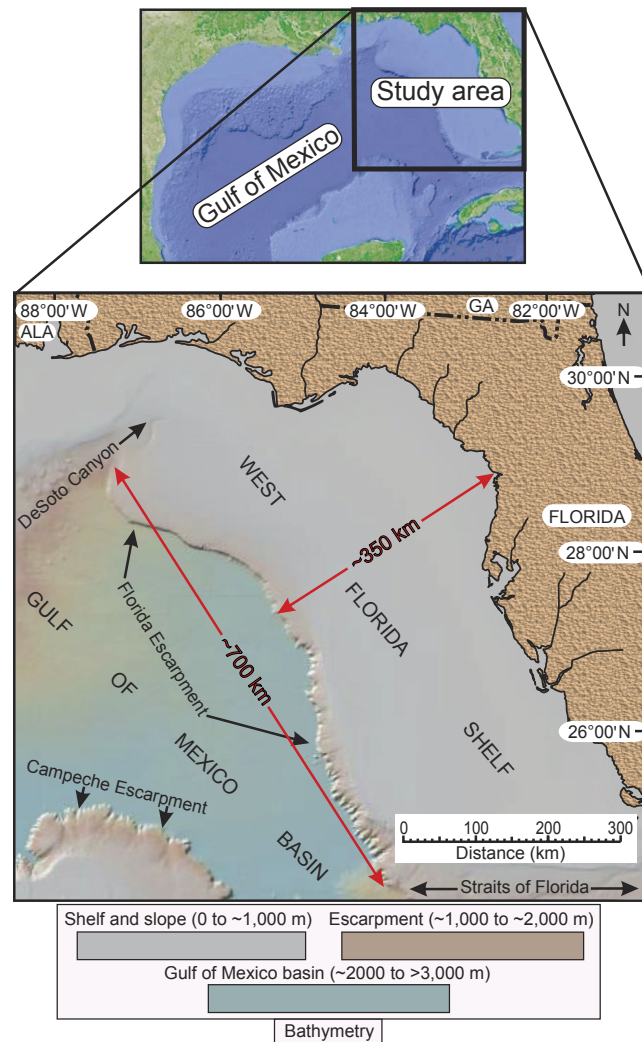


Figure 2. Principal physiographic features of the study area, offshore Florida (Gulf of Mexico). ALA—Alabama; GA—Georgia.

TABLE 1. SEISMIC SURVEYS USED IN THIS STUDY

Survey name	Number of lines	Line km collected	Year collected	Migrated
4 Series	135	8110	1974	No
USGS	3	298	1979	Yes
Pr83	4	1817	1983	Yes
SFB	30	5273	1984	No
GWT86	33	6446	1986	Yes
DFM	81	14,588	1986	No
Dv88	41	3873	1988	Yes
Totals	327	40,405		

Note: See Figure 3 for survey locations.

TABLE 2. DEEP INDUSTRY BOREHOLES USED IN THIS STUDY

Borehole name	General location	Total depth (m)	Stratigraphic level at total depth
Mobil 3886-1	Apalachicola Basin	7091	Middle Jurassic (salt)
Gulf 2468-1	Apalachicola Basin	6397	Upper Jurassic (Tithonian)
Tenneco 6391-1	Apalachicola Basin	5852	Upper Jurassic (Oxfordian)
Exxon 2486-3	Apalachicola Basin	5468	Upper Jurassic (Oxfordian)
Exxon 6428-1	Apalachicola Basin	5334	Lower Cretaceous (Valanginian)
Amoco 2502-1	Apalachicola Basin	5589	Middle Jurassic (salt)
Sun 2490-1	Apalachicola Basin	5367	Paleozoic (basement)
Shell 6417-1	Apalachicola Basin	5414	Lower Cretaceous (Valanginian)
Chevron 6438-1	Apalachicola Basin	6773	Middle Jurassic (Callovian?)
Sohio 3890-1	Apalachicola Basin	6419	Upper Jurassic (Tithonian?)
Tenneco 8363-1	Middle Ground Arch	3789	Lower Cretaceous (Aptian?)
Texaco 2516-1	Middle Ground Arch	4770	Paleozoic (Ordovician)
Sohio 6456-1	Middle Ground Arch	4860	Paleozoic (basement)
Calco 224-A2	Middle Ground Arch	3208	Triassic
Shell 2527-1	Tampa Embayment	5623	Paleozoic (basement)
Texaco 2523-1	Tampa Embayment	5295	Paleozoic (Mississippian)
Mobil 3344-1	Tampa Embayment	4836	Upper Jurassic
Calco 224-B3	Tampa Embayment	3231	Triassic
Mobil 3341-1	Tampa Embayment	5524	Paleozoic (basement)
Shell 3912-1	Sarasota Arch	3850	Paleozoic (basement)
Odeco 3909-1	Sarasota Arch	3463	Paleozoic (basement)
Gulf 3906-1	Sarasota Arch	3464	Paleozoic (basement)
Mobil 3903-1	Sarasota Arch	3282	Paleozoic (basement)
Mobil 3915-1	Sarasota Arch	3435	Paleozoic (basement)
Mobil 224-B1	Sarasota Arch	3837	Paleozoic (basement)
Shell 4950-1	Sarasota Arch	3216	Paleozoic (basement)
Tenneco 3917-1	Sarasota Arch	3445	Paleozoic (basement)
Calco 224-B1	Sarasota Arch	3837	Paleozoic (basement)

Note: Borehole data can be accessed online from the U.S. Bureau of Ocean Energy Management (<https://boem.gov>). See Figure 3 for borehole locations.

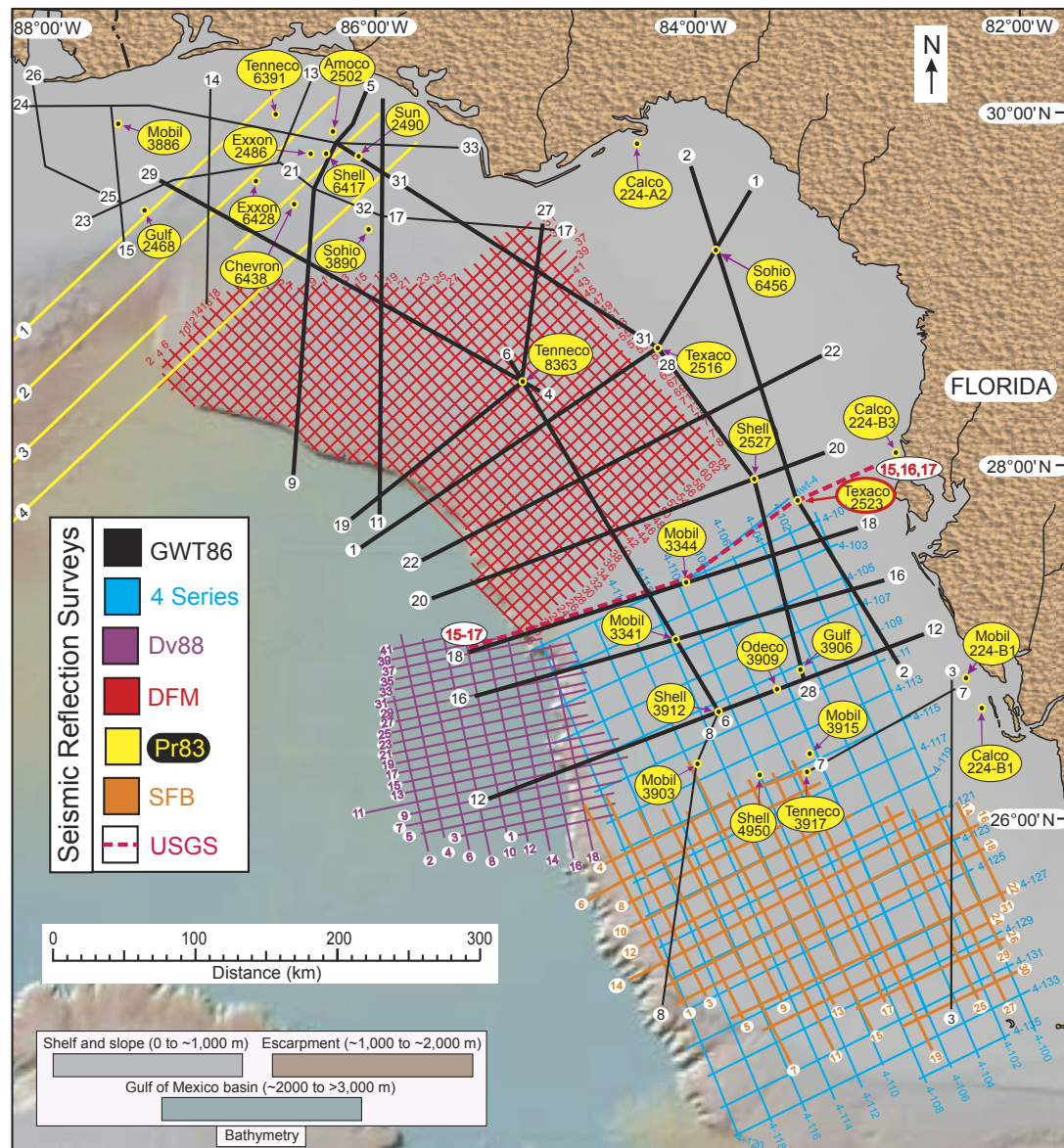


Figure 3. Location of seven different sets of seismic reflection surveys (327 total lines) and 28 deep industry boreholes used in this study. Profiles represented by heavier black lines (subset of GWT86 profiles) form the primary basis for the general stratigraphic and structural framework.

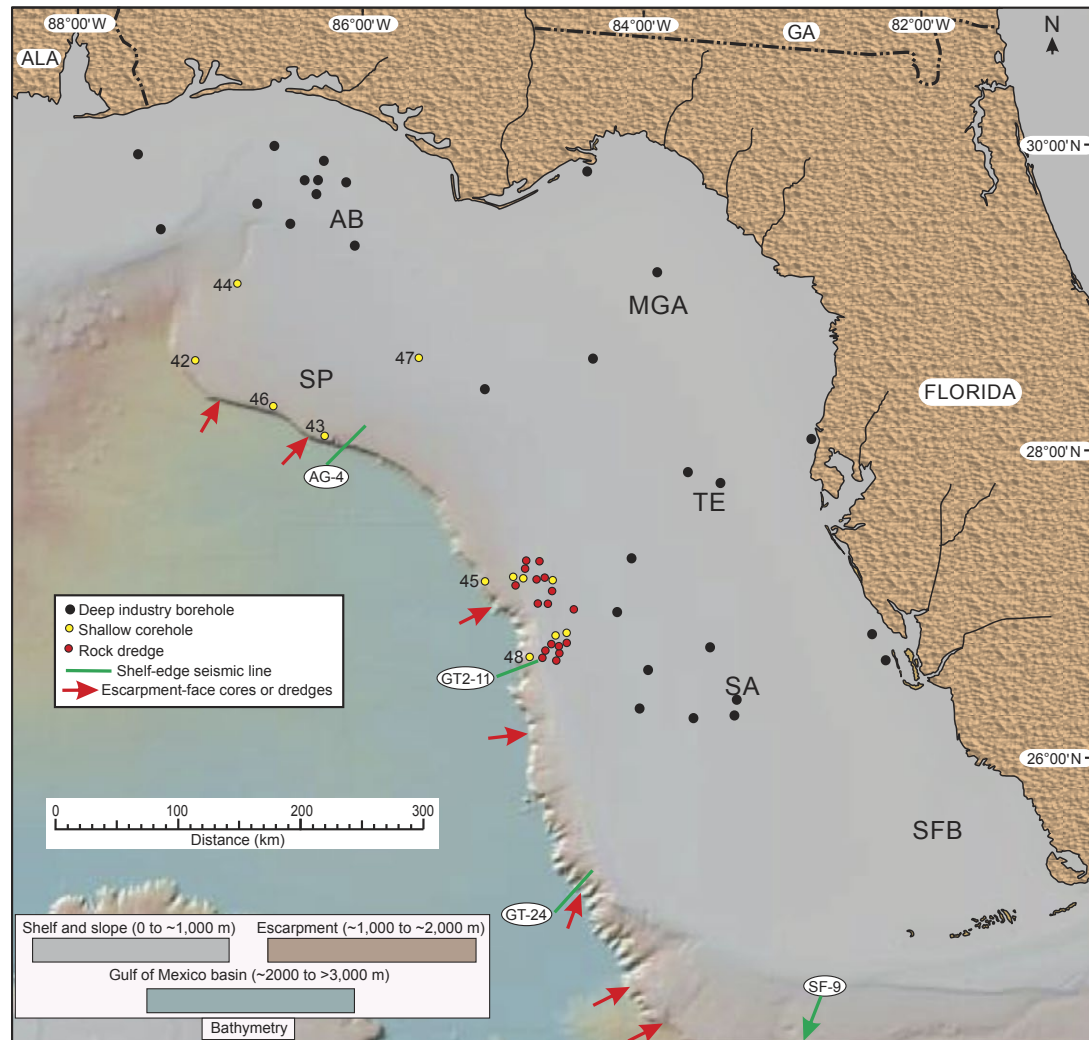


Figure 4. Location of deep industry boreholes, shallow gravity and piston core sites, dredge sites, short shelf-edge seismic reflection lines, and escarpment-face cores and dredges. Numbered shallow coreholes are from Mitchum (1978); non-numbered shallow coreholes and rock dredges are from Mullins et al. (1988a, 1988b); shelf-edge seismic lines are from Corso et al. (1988); escarpment-face cores and dredges are from Freeman-Lynde (1983) and Paull et al. (1990). ALA—Alabama; GA—Georgia; AB—Apalachicola Basin; SP—Southern Platform; MGA—Middle Ground Arch; TE—Tampa Embayment; SA—Sarasota Arch; SFB—South Florida Basin.

The most recent regional studies of the West Florida Platform are unpublished theses of Dobson (1990) and Jee (1993), both of which covered its central and northwestern segments and emphasized seismostratigraphic sequence analysis. Dobson (1990) investigated pre-Jurassic and Jurassic sections and later published the principal results (Dobson and Buffler, 1991, 1997). Jee (1993) focused on Upper Cretaceous and Paleogene intervals, with emphasis on Eocene rocks; a few of his results were published by Randazzo (1997).

Widespread karstification of Cenozoic strata precludes high-quality seismic reflection data from Mesozoic strata in the southeastern segment of the West Florida Platform, and no previous comprehensive studies of that segment have been published. However, several authors have published more localized studies in that area (Shaub, 1984; Macurda, 1988; Denny et al., 1994).

A wide variety of additional studies focused on specific geographic areas and stratigraphic intervals of the West Florida Platform as well as adjacent coastal Florida. Cretaceous studies include Winston (1971, 1978), Applegate et al. (1982), Freeman-Lynde (1983), Applegate and Pontigo (1984), Applegate (1987), Corso (1987), Corso et al. (1988, 1989), Mullins et al. (1988b), Faust (1990), Paull et al. (1990, 1991), Gardulski et al. (1991), Hine (1997), and Randazzo (1997). Previous reports related to Chicxulub impact deposits in the eastern Gulf of Mexico include Dohmen (2002), Denne et al. (2013), Sanford et al. (2016), and Poag (2017). No specific studies of the Eocene section of the West Florida Platform have been published.

■ PHYSIOGRAPHY

Previous authors generally described the West Florida Platform as having been a rimmed carbonate shelf during most of Early Cretaceous time (Bryant et al., 1969; Corso, 1987; Hine, 1997; Randazzo, 1997; Hine and Locker, 2011; Snedden and Galloway, 2019). Mullins et al. (1988a, 1988b) described the outer part of the modern shelf as a ramp slope, which began to develop in the late Oligocene. At its widest point, the modern “shelf” segment of the West Florida Platform slopes gently southwestward from the Florida shoreline to ~250 km offshore (Fig. 5). There (~200 m water depth), a notable increase in seafloor inclination marks the inner edge of the ramp slope. Seafloor inclination increases dramatically ~300 km from shore (~1.5–2 km water depth) at the lip of the escarpment as it plunges to ~2–3 km below sea level. These aspects, especially shelf and slope width, seafloor morphology, escarpment height, and roughness of the escarpment face, exhibit moderate to notable variability along depositional strike (e.g., Twichell et al., 1990; Figs. 6–12). Locker and Buffler (1983) reported a range of ~15° to ~40° for the escarpment slope angle at three locations near 27°00'N, whereas Paull et al. (1991) reported roughly 60° slope angles at three locations near 25°00'N. Using vertical exaggeration of generally 13:1, my data from 12 locations along the escarpment indicate slope angles of ~75°–80°; with no vertical exaggeration, slope angles range from ~15° to 55° (Table 3). The escarpment face is only moderately rough along its northwestern

segment, cut by numerous small ravines (Twichell et al., 1990; Fig. 6A), but the southeastern segment is steep, jointed, terraced, and notched by numerous deep box canyons and shallow gullies (Fig. 6B). Canyon walls are terraced as well and are cut, in turn, by multiple series of linear gullies (Fig. 7; Paull et al., 1990, 1991). Thick Cenozoic bathyal clastics bury the escarpment base (Paull et al., 1990, 1991; Galloway et al., 1991) and bury the entire escarpment at its northwestern and southeastern extremities (Fig. 8A).

■ LOWER CRETACEOUS ROCKS

Lower Cretaceous rocks and underlying Upper Jurassic strata constitute, by far, the thickest depositional units of the West Florida Platform, and the Lower Cretaceous section dominates outcrops on the Florida Escarpment. The Lower Cretaceous section reaches as thick as 4000 m in boreholes of the Apalachicola Basin (e.g., borehole Sohio 3890-1; Fig. 3; Fig. S1¹) but thins to ~900 m in nearshore boreholes (Table 4). Seismic data indicate similar thick sections in undrilled downdip regions. For example, Dobson and Buffler (1991) estimated ~4000 m of Lower Cretaceous section at the downdip margin of the Tampa Embayment approximately along seismic line GWT86-1 (Fig. 3; Fig. S2 [footnote 1]). Despite the major importance of Lower Cretaceous rocks in the stratigraphic and paleoenvironmental development of the West Florida Platform, few detailed regional studies address these rocks, though several important more localized studies are available (e.g., Addy and Buffler, 1984; Applegate, 1987; Corso et al., 1988, 1989; Locker and Buffler, 1983; MacRae and Watkins, 1992; Randazzo, 1997). McFarlan and Menes (1991) and Snedden and Galloway (2019) included generalized regional reviews of this stratigraphic interval for the entire Gulf of Mexico.

Depending on the type of data applied (microfossil and sedimentological samples versus seismic reflection data), interpretations of end-Cretaceous depositional disruption have reached opposing conclusions regarding escarpment origin and paleoenvironments.

Microfossil and Sedimentological Samples

Researchers have collected 119 scattered samples of litho- and biofacies from the Florida Escarpment. Because most samples lack evidence of platform-margin paleoenvironments, Freeman-Lynde (1983) and Paull et al. (1990) concluded that much of the original margin of the platform must have been eroded shoreward, possibly by ~5–10 km. However, only six of these 119 samples contained Early Cretaceous (Aptian, Albian) foraminifera and nanofossils (Antoine et al., 1967; Bryant et al., 1969; Freeman-Lynde, 1983;

¹Supplemental Material. Figures S1–S9. Stratigraphic interpretations of seismic reflection profiles GWT86-11, GWT86-1, GWT86-16, GWT86-18, GWT86-9, GWT86-11, GWT86-19, GWT86-1, and GWT86-20, respectively. Please visit <https://doi.org/10.1130/GEOS.S.19149428> to access the supplemental material, and contact editing@geosociety.org with any questions.

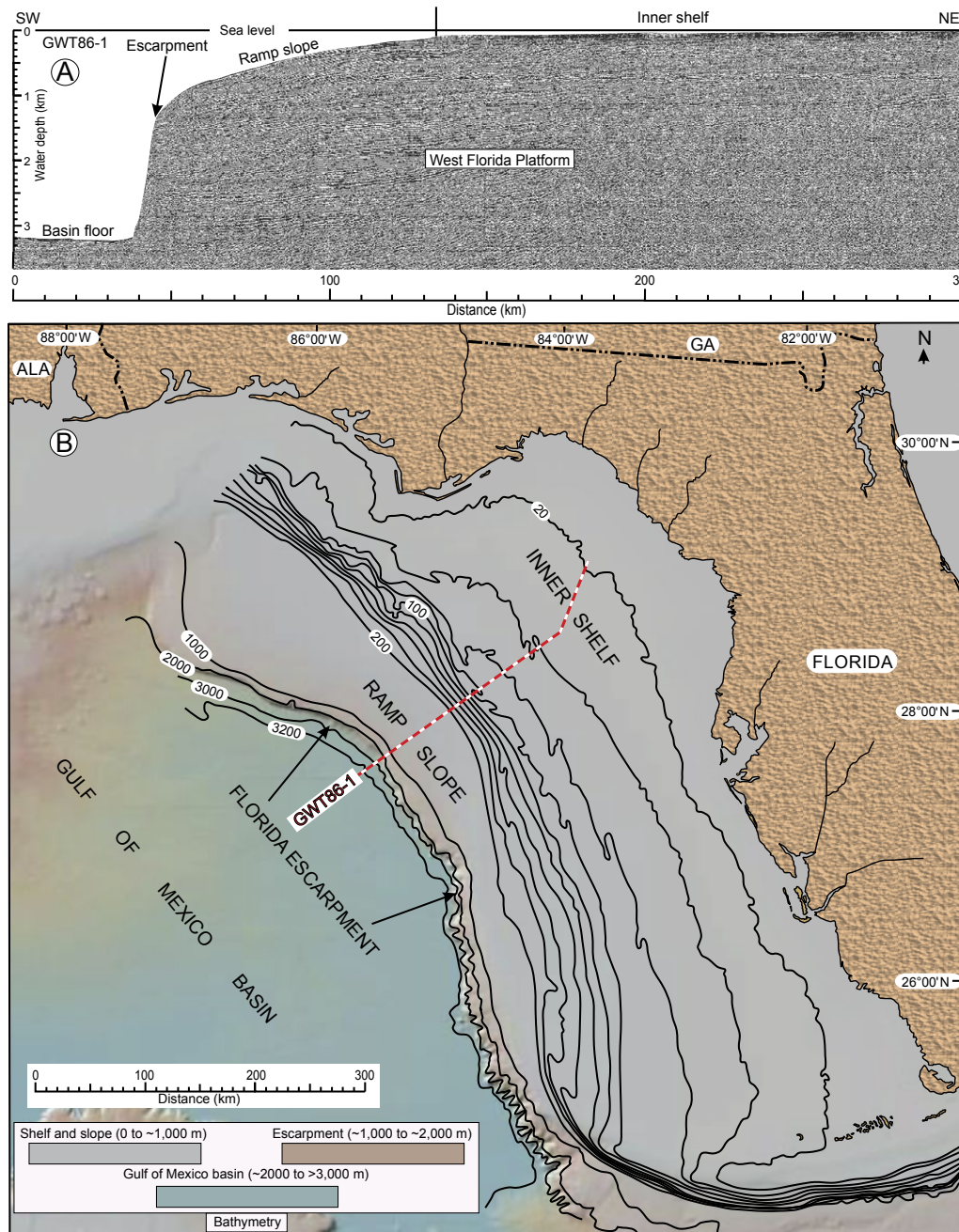


Figure 5. Physiography of the modern seafloor of the West Florida Platform. (A) Silhouette of seismic reflection line GWT86-1 shows four major physiographic regions; vertical exaggeration at seafloor is 20:1. (B) Bathymetric contours across the West Florida shelf (inner shelf), West Florida slope (ramp slope), and Florida Escarpment illustrate variation in inclination of the seafloor from northeast to southwest. Contours are in meters; interval is variable. ALA—Alabama; GA—Georgia.



Figure 6. Bathymetric shaded-relief imagery of the West Florida slope and Florida Escarpment illustrates the contrast between the moderate roughness of the escarpment in the northwestern segment (A) and numerous canyons and gullies of the southeastern segment (B). Note that a prominent notch marks the approximate lateral midpoint of the escarpment; canyon size and depth increase southeast of the notch. Bathymetry is from Google Earth.

Paull et al., 1990). Furthermore, none contained Jurassic microfossils, though seismic data indicate that Jurassic rocks crop out at several places along the escarpment face. Six Lower Cretaceous samples from the roughly 900 km² exposed on this escarpment are clearly not representative of the entire out-crop. Much more sampling is required for a conclusive paleoenvironmental interpretation.

Seismic Reflection Data

In contrast to Freeman-Lynde (1983) and Paull et al. (1990), Locker and Buffler (1983) interpreted the escarpment's seismic signature to represent a platform-edge reef barrier. Corso et al. (1988) agreed that chaotic seismic reflections and diffraction hyperbolae at two locations across the escarpment

edge indicated the presence of reefal platform-margin facies. Corso et al. (1988) also concluded that the original platform edge had eroded shoreward ~5–10 km during a ~40 m.y. interval from mid-Cenomanian through late Paleocene time. These authors used a geometric method to derive the amount of retreat. They estimated the distance between the base of the modern escarpment and the point at which a prominent couplet of seismic reflections truncates the top of the Early Cretaceous “toe-of-slope” facies (Fig. 13). They correlated this seismic couplet with a “mid-Cretaceous unconformity” or “mid-Cretaceous sequence boundary,” which was widely recognized across the deep Gulf of Mexico basin. However, later studies (Dohmen, 2002; Denne et al., 2013; Sanford et al., 2016; Poag, 2017) have shown conclusively that the so-called “mid-Cretaceous unconformity” represents the final pelagic facies of an enormous gulf-wide body of sediment (>198 × 10³ km³; Sanford et al., 2016) derived from widespread effects of the Chicxulub bolide impact. Thus, the Early Cretaceous

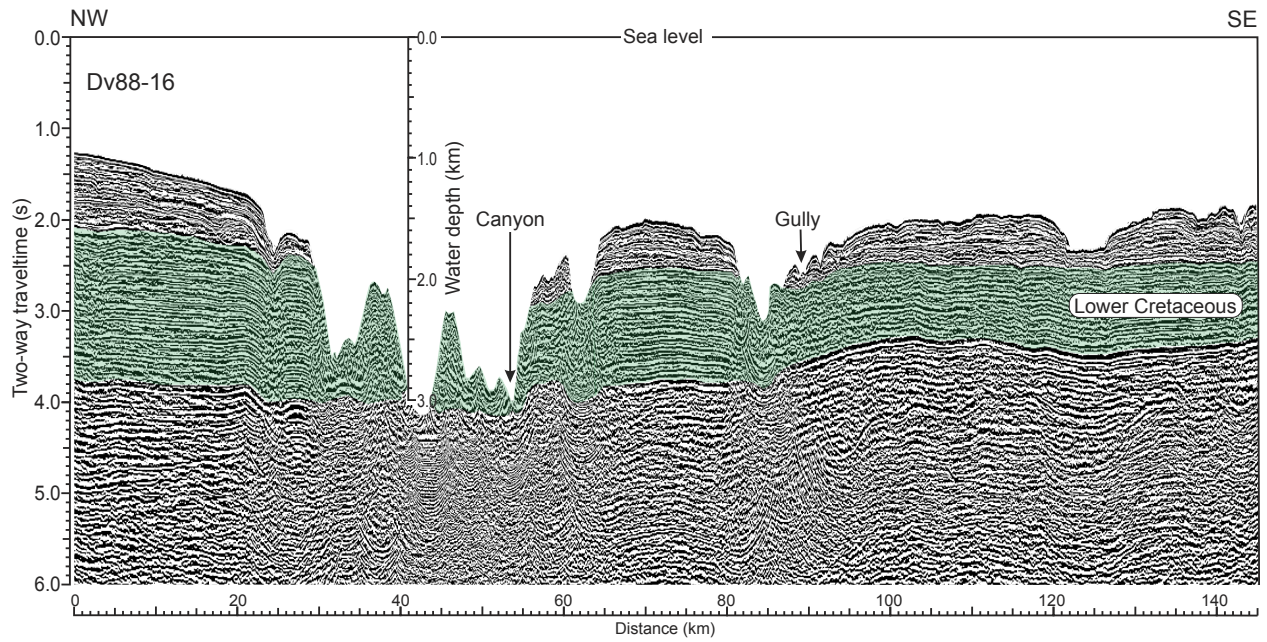


Figure 7. Seismic reflection line Dv88-16, parallel to depositional strike (see Fig. 3 for location), shows extensive erosional canyons and gullies along the southeastern segment of the West Florida Platform and extensive removal of Lower Cretaceous and younger strata. Vertical exaggeration is ~15:1 at seafloor.

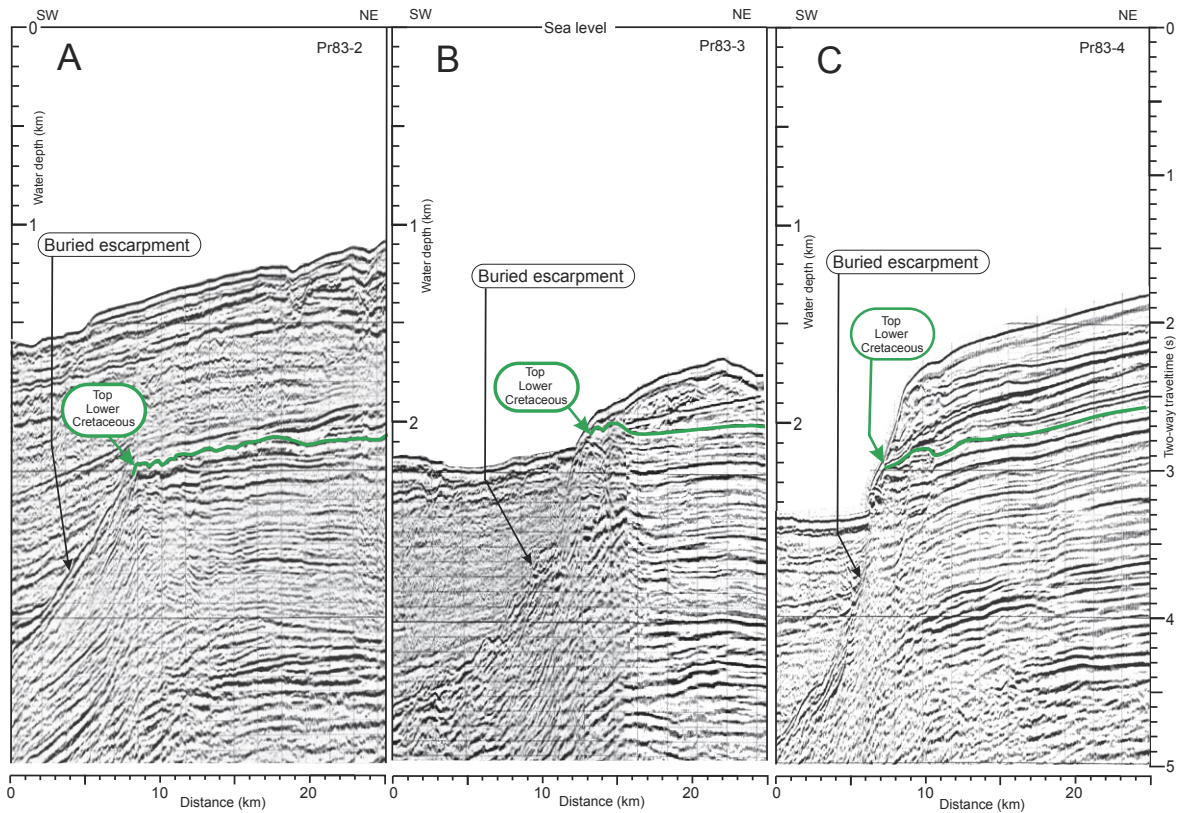


Figure 8. Seismic reflection lines Pr83-2, Pr83-3, and Pr83-4 at the northwestern end of the study area (see Fig. 3 for location) show the profile of the Florida Escarpment in a southeastward progression from complete burial (A) to an exposed height of ~0.7 km (C). Vertical exaggeration is ~13:1 at seafloor.

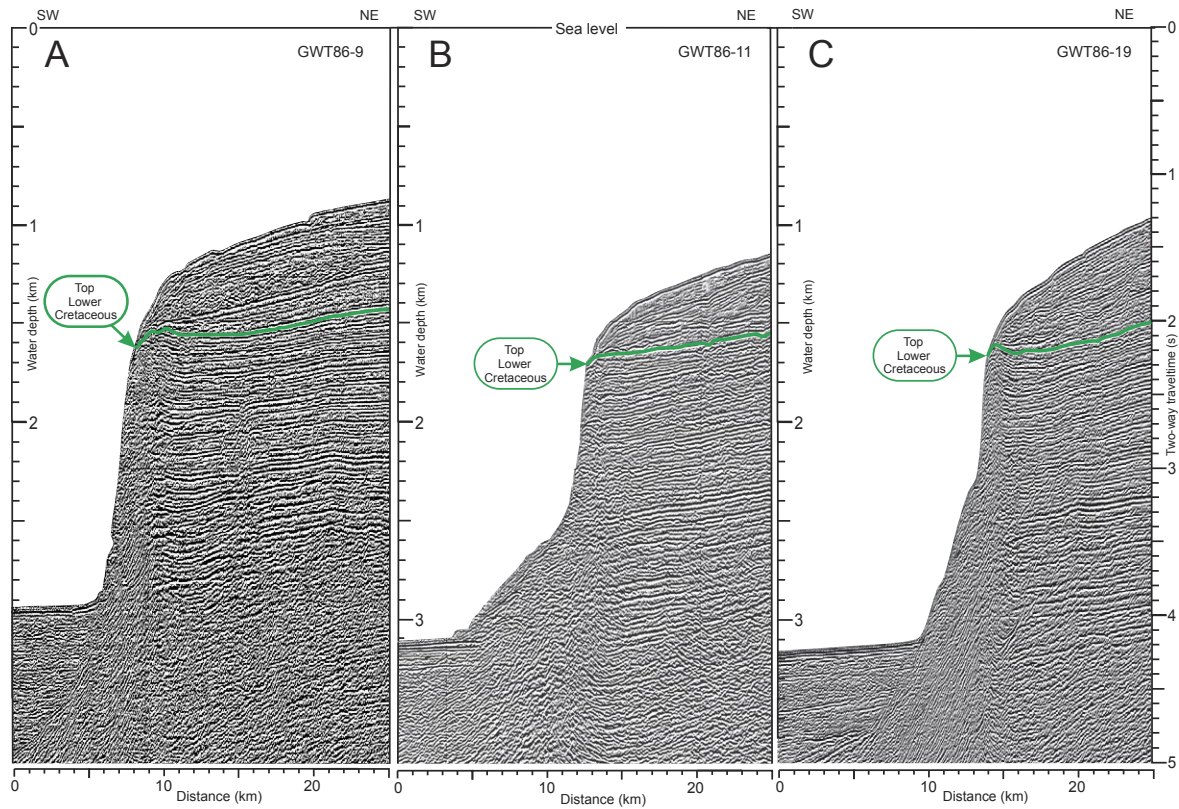


Figure 9. Seismic reflection lines GWT86-9, GWT86-11, and GWT86-19 (see Fig. 3 for location) show southeastward variation of the exposed height and profile of the Florida Escarpment and the position of the top of Lower Cretaceous strata. Escarpment height ranges from ~1.6 km (B) to ~1.7 km (A, C) along this segment. Vertical exaggeration is ~13:1 at seafloor.

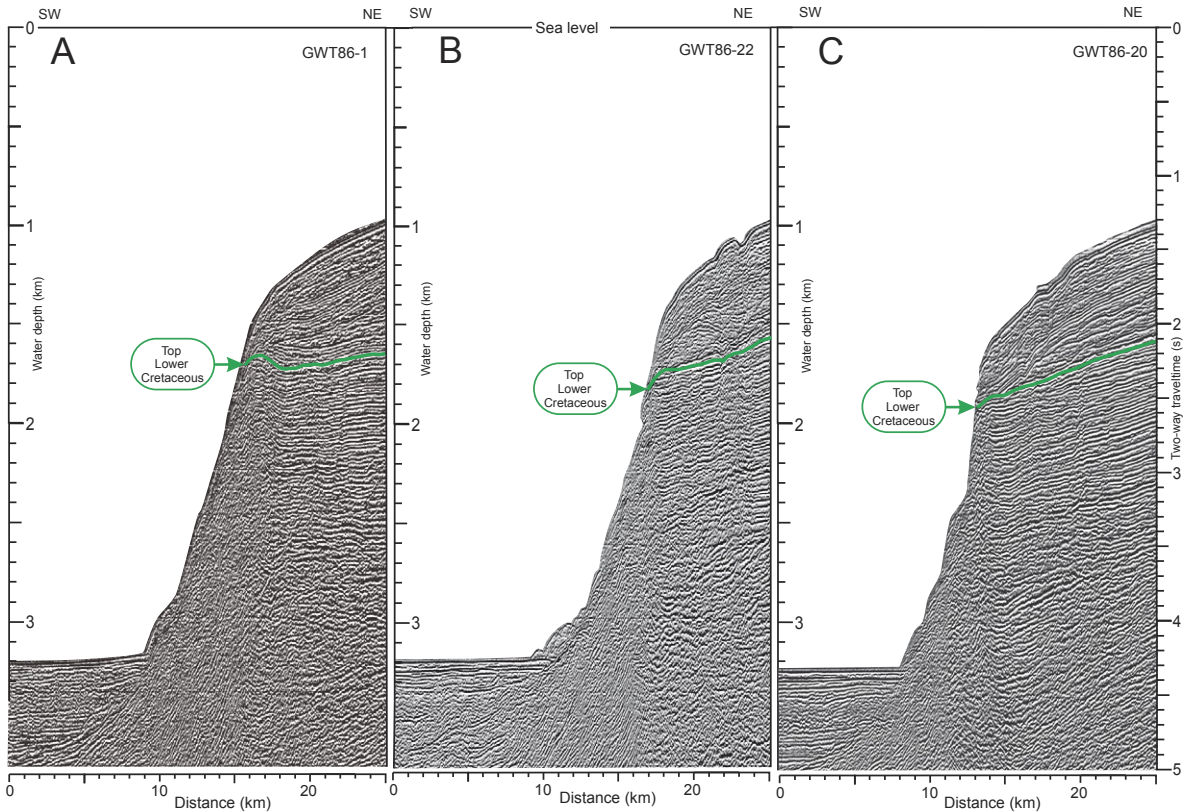


Figure 10. Seismic reflection lines GWT86-1, GWT86-22, and GWT86-20 (see Fig. 3 for location) show southeastward variation of escarpment height and profile and the position of the top of Lower Cretaceous strata. Escarpment height ranges from ~1.6 km (C) to ~1.9 km (A) along this segment. Vertical exaggeration is ~13:1 at seafloor.

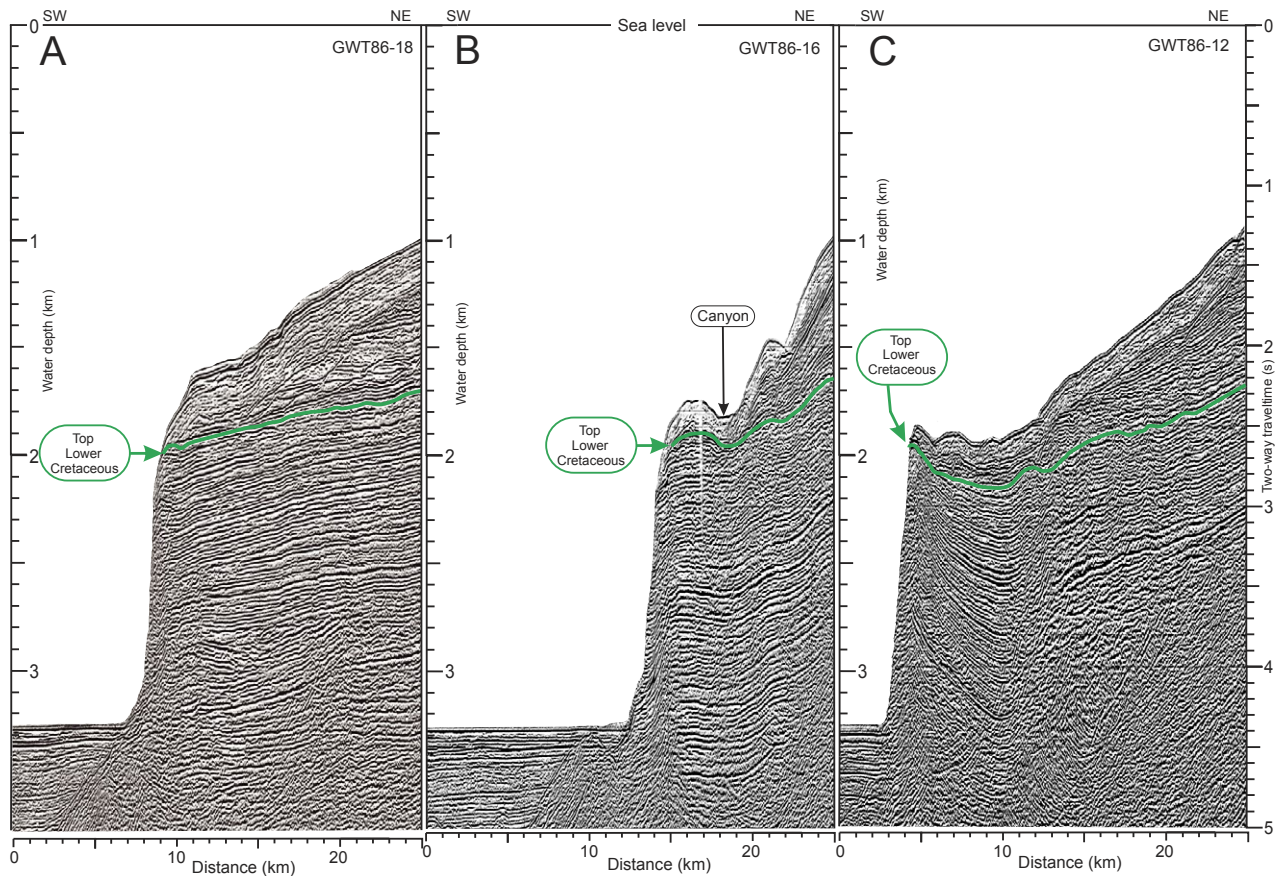


Figure 11. Seismic reflection lines GWT86-18, GWT86-16, and GWT86-12 (see Fig. 3 for location) show southeastward variation of the escarpment profile as the platform margin begins to exhibit extensive canyon and gully erosion. Escarpment height ranges from ~1.4 km (C) to ~1.6 km (A). Vertical exaggeration is ~13:1 at seafloor.

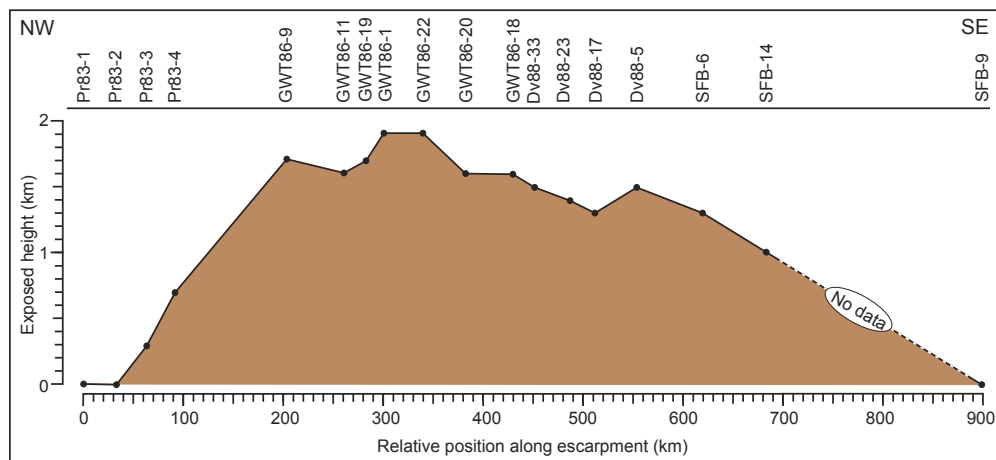


Figure 12. Chart of exposed escarpment height at 18 locations (see Fig. 3) along a northwest-southeast transect shows maximum height (as measured from the top of Lower Cretaceous strata) in the central region but complete burial at both extremities.

TABLE 3. ESCARPMENT SLOPE ANGLE VERSUS VERTICAL EXAGGERATION IN SEISMIC PROFILES

Seismic line	Vertical exaggeration	Slope angle (degrees)
Pr83-4	13:1	~75
	1:1	~15
GWT86-9	13:1	~80
	1:1	~30
GWT86-11	13:1	~75
	1:1	~30
GWT86-19	13:1	~75
	1:1	~40
GWT86-1	13:1	~75
	1:1	~20
GWT86-22	13:1	~75
	1:1	~20
GWT86-20	13:1	~75
	1:1	~40
GWT86-18	13:1	~80
	1:1	~55
GWT86-16	13:1	~80
	1:1	~50
GWT86-12	13:1	~85
	1:1	~45
Dv88-33	20:1	~80
	1:1	~45
SFB-14	8:1	~60
	1:1	~20

Note: See Figure 3 for seismic line locations.

“toe-of-slope” facies of Corso et al. (1988) and its capping seismic couplet compose part of what many researchers have called the Cretaceous-Paleogene boundary deposit (e.g., Sanford et al., 2016; Snedden and Galloway, 2019). This terminology is misleading because the International Commission on Stratigraphy (Molina et al., 2006) has redefined the Cretaceous-Paleogene boundary and assigned all deposits resulting from the Cretaceous-ending impact to the earliest Paleocene. Because the chronostratigraphic terminology applied to this unit is potentially subject to future change, I prefer to tie it to a specific geologic event and call it the Chicxulub impact deposit (Fig. 13). Though the Chicxulub impact deposit in the Gulf of Mexico contains abundant Cretaceous-age debris, that debris was redistributed and deposited during the earliest Paleocene. This means that the false “mid-Cretaceous unconformity” of the basin is not equivalent to the genuine mid-Cretaceous unconformity of the escarpment. These relationships mandate modification of the Corso et al. (1988) method of measuring escarpment-retreat distance.

TABLE 4. LOWER CRETACEOUS SECTION IN BOREHOLES

Borehole name	General location	Section thickness (m)	Accumulation rate (m/m.y.)
Mobil 3886-1	Apalachicola Basin	2786	62
Gulf 2468-1	Apalachicola Basin	3264	73
Tenneco 6391-1	Apalachicola Basin	2843	63
Exxon 2486-3	Apalachicola Basin	1570	35
Exxon 6428-1	Apalachicola Basin	3088	69
Amoco 2502-1	Apalachicola Basin	2283	51
Sun 2490-1	Apalachicola Basin	991	22
Shell 6417-1	Apalachicola Basin	3920	87
Chevron 6438-1	Apalachicola Basin	3008	67
Sohio 3890-1	Apalachicola Basin	3944	88
Tenneco 8363-1	Middle Ground Arch	2079	45
Texaco 2516-1	Middle Ground Arch	2050	45
Sohio 6456-1	Middle Ground Arch	1273	28
Calco 224-A2	Middle Ground Arch	?	?
Shell 2527-1	Tampa Embayment	1936	43
Texaco 2523-1	Tampa Embayment	1807	40
Mobil 3344-1	Tampa Embayment	2414	54
Calco 224-B3	Tampa Embayment	1032	23
Mobil 3341-1	Tampa Embayment	2207	49
Shell 3912-1	Sarasota Arch	1542	34
Odeco 3909-1	Sarasota Arch	1384	31
Gulf 3906-1	Sarasota Arch	999	22
Mobil 3903-1	Sarasota Arch	?	?
Mobil 3915-1	Sarasota Arch	?	?
Mobil 224-B1	Sarasota Arch	?	?
Shell 4950-1	Sarasota Arch	1249	28
Tenneco 3917-1	Sarasota Arch	988	22
Calco 224-B1	Sarasota Arch	?	?

Note: See Figure 3 for borehole locations; see Table 2 for additional borehole data. Question mark indicates data not available.

In light of this new interpretation, I propose a method to estimate “minimum escarpment retreat” (MER). It is similar to the method of Corso et al. (1988) but measures the lateral distance between the modern location of the platform margin (i.e., the top of the Lower Cretaceous escarpment) and the estimated position of the base of the escarpment prior to deposition of the Chicxulub impact deposit (roughly the base of the preserved Jurassic platform margin; Fig. 13).

The estimate is *minimum* because, presumably, part of the Jurassic platform margin would have been removed as well. However, the platform-edge position of the Upper Jurassic section is not always clearly evident. My measurements indicate average MER of ~7 km, ranging from ~3 to ~10 km (Table 5). Greatest MER (~10 km) is indicated for seismic lines Dv88-33 and GWT86-16 (Fig. S3 [footnote 1]). All MER values are approximate, however, because seismic data are partly obscured by chaotic reflections (hyperbolic diffractions, velocity pullups) on most cited lines. Dillon et al. (1988) applied

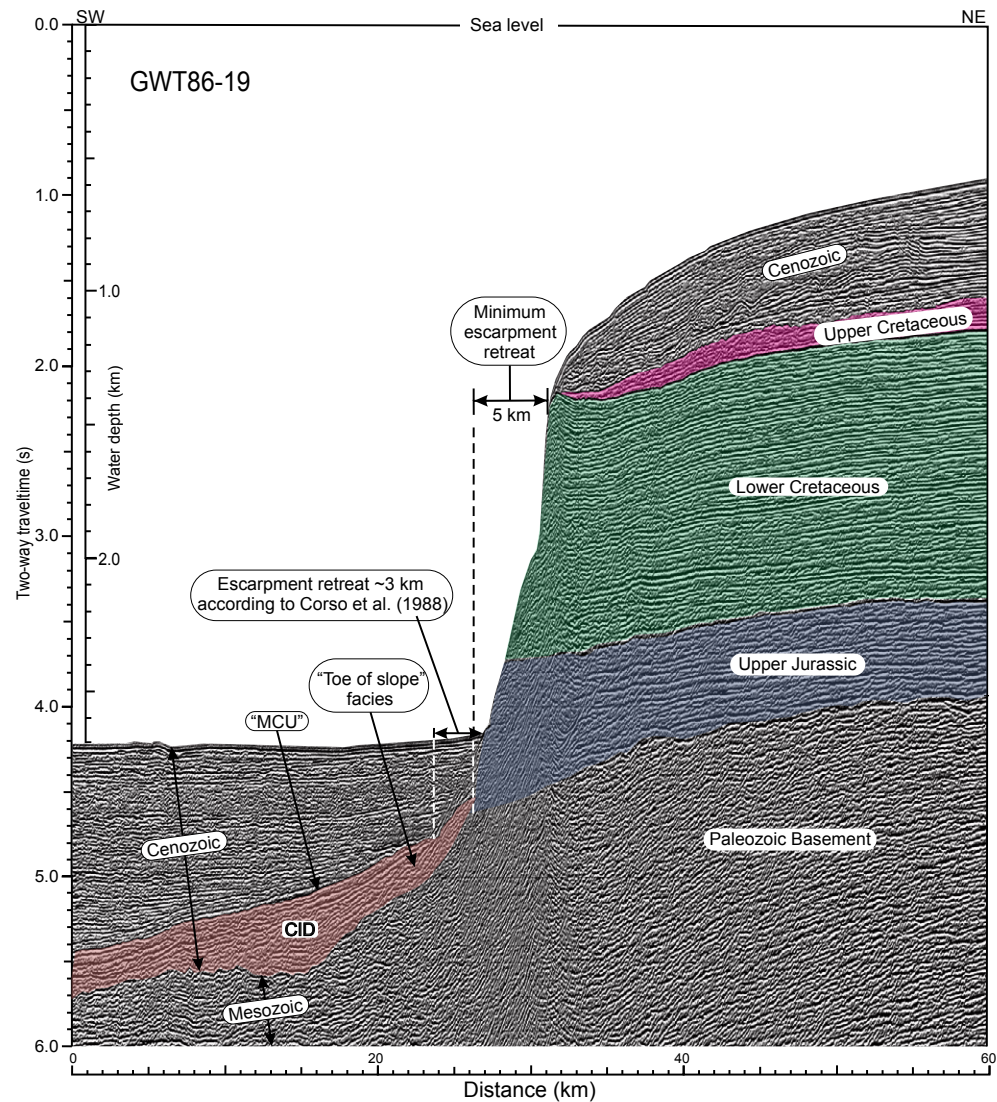


Figure 13. Platform-edge portion of seismic reflection line GWT86-19 (see Fig. 3 for location) compares the method used by Corso et al. (1988) to estimate the distance of escarpment retreat to the minimum escarpment retreat method used herein. CID—Chicxulub impact deposit; “MCU” — mid-Cretaceous unconformity, the original terminology applied to the top layer of the CID. Vertical exaggeration is ~17:1 at seafloor.

TABLE 5. HEIGHT AND RETREAT OF THE FLORIDA ESCARPMENT

Seismic line	Original height (s TWTT)	Original height (km)	Exposed height (km)	Minimum retreat (km)
Pr83-2	~1.0	~1.5	0	~3
Pr83-3	~2.2	~3.5	~0.2	~5
Pr83-4	~2.5	~3.5	~0.6	~6
GWT86-9	~2.8	~4.0	~1.7	~6
GWT86-11	~2.5	~3.5	~1.6	~8
GWT86-19	~2.4	~3.5	~1.7	~8
GWT86-1	~3.4	~5.0	~1.9	~8
GWT86-22	~3.0	~5.0	~1.9	~8
GWT86-20	~2.8	~4.0	~1.6	~8
GWT86-18	~2.8	~4.5	~1.6	~8
Dv88-33	~2.6	~4.0	~1.5	~10
GWT86-16	~3.0	~4.0	~1.4	~10
Dv88-25	~3.3	~4.0	~1.5	~8
Dv88-19	~3.5	~4.0	~1.5	~6
GWT86-12	~3.5	~4.0	~1.2	~8
Dv88-5	~3.8	~4.0	~1.5	~8
SFB-9	~1.2	~2.5	0	~3

Note: See Figure 3 for seismic line locations. TWTT—two-way traveltime. Minimum retreat is measured as the lateral distance between the top of the Lower Cretaceous outcrop on the Florida Escarpment and the landward edge of the Chicxulub impact deposit (CID); see Figure 13.

synthetic seismograms to demonstrate, for example, that the actual location of an escarpment face corresponds approximately to the apices of the hyperbolic diffractions, significantly shoreward (by several kilometers) of its apparent location on the seismic reflection image (Fig. 14).

Most authors (e.g., Corso et al., 1988; Paull et al., 1990) have concluded that shoreward retreat of the platform edge took place through relatively slow-acting biological, chemical, and gravitational processes of erosion. However, recent documentation of the far-reaching effects of the Chicxulub bolide impact give reason to consider a more rapid retreat process. For example, Paull et al. (2014) concluded that massive margin collapse of the nearby Campeche Escarpment must have contributed significantly to the broad breccia-rich sediment apron flanking the escarpment and suggested that a collapse of the Florida Escarpment produced a similar sediment apron. These authors documented the presence of large megablocks (~2 km wide) within the apron deposits, inferring their original source to have been the escarpment face. Two seismic reflection profiles across the northwestern flank of the Campeche Platform published by Locker and Buffler (1983) imaged the Chicxulub impact deposit there (Figs. 15, 16). Line GT3-60 (Fig. 16) documents large slump blocks (~10 km in length) in the impact deposit, expressing parallel, stratified seismic facies. They appear to have been derived from the Late Cretaceous escarpment face.

Numerical modeling indicates that seismic shaking and ground roll from Chicxulub would have produced >1 m of vertical motion on the West Florida

TABLE 6. EOCENE SECTION IN BOREHOLES

Borehole name	General location	Section thickness (m)	Accumulation rate (m/m.y.)
Mobil 3886-1	Apalachicola Basin	329	14
Gulf 2468-1	Apalachicola Basin	46	2
Exxon 2486-3	Apalachicola Basin	201	8
Exxon 6428-1	Apalachicola Basin	412	17
Amoco 2502-1	Apalachicola Basin	442	18
Shell 6417-1	Apalachicola Basin	146	6
Chevron 6438-1	Apalachicola Basin	265	11
Sohio 3890-1	Apalachicola Basin	403	17
Tenneco 8363-1	Middle Ground Arch	438	18
Texaco 2516-1	Middle Ground Arch	729	30
Sohio 6456-1	Middle Ground Arch	610	25
Shell 2527-1	Tampa Embayment	1244	52
Texaco 2523-1	Tampa Embayment	768	32
Mobil 3344-1	Tampa Embayment	1197	50
Calco 224-B3	Tampa Embayment	854	36
Mobil 3341-1	Tampa Embayment	1146	48
Shell 3912-1	Sarasota Arch	1268	53
Odeco 3909-1	Sarasota Arch	603	25
Gulf 3906-1	Sarasota Arch	213	9
Shell 4950-1	Sarasota Arch	457	19
Tenneco 3917-1	Sarasota Arch	663	28
Calco 224-B1	Sarasota Arch	750	31
Mitchum core 43	Outer ramp slope	120	5
Mitchum core 46	Outer ramp slope	70	3

Note: Mitchum cores were drilled by a consortium of four oil companies (Exxon, Chevron, Gulf, and Mobil). Mitchum core 43 is located at 28°00' N; 86°25' W, and core 45 is located at 27°10' N; 85°16' W.

Platform within five minutes of impact, followed in ~1 h by tsunami-driven erosion and sediment redistribution (Sanford et al., 2016). These mechanisms severely disrupted Upper Cretaceous strata over ~64 × 10³ km² of the West Florida Platform, reaching as far as 180 km shoreward of the escarpment (Figs. 17A, 17B; Poag, 2017). A potential sediment volume of ~4–5 × 10³ km³ was redistributed from the platform interior to the Chicxulub impact deposit apron bordering the escarpment. These circumstances imply that a significant amount of platform-edge erosion must also have incorporated instantaneous, impact-related processes operating in the final moments of the Cretaceous. The resultant debris, represented in part by chaotic, discontinuous, high-amplitude seismic reflections in the Chicxulub impact deposit (“toe-of-slope” facies), accumulated in the earliest moments of the first day of the Paleocene (Gulick et al., 2019). The Chicxulub impact site’s relatively close proximity (~600 km) to the southeastern end of the West Florida Platform (Fig. 18A) would account for the extensive jointing and canyon cutting along this southeastern part of the escarpment. Florida Canyon, the deepest and longest escarpment canyon, is located there (Fig. 18B).

■ EOCENE ROCKS

Eocene strata are well documented on the Florida peninsula (Chen, 1965; Miller, 1986; Randazzo, 1997) and are dominantly inner to middle neritic carbonates. In contrast, the only specific study of Eocene strata of the West Florida Platform is the unpublished Ph.D. thesis of Jee (1993). However, Mitchum (1978) and Mullins et al. (1988b) included analyses of Eocene strata in core samples derived from the outer part of the Eocene ramp slope, which consisted mainly of pelagic deposits dominated by foraminifera-nannofossil ooze or chalk

(Gardulski et al., 1991). On the other hand, the Eocene section updip on the shelf, such as in the Texaco 2523-1 borehole, contains mainly dolomitic inner neritic deposits dominated by benthic foraminifera (Fig. 19). The paleogeography of the Eocene section differs strongly from that of the Lower Cretaceous section in that the shelf edge is not located at the escarpment but as much as 100 km or more updip of the escarpment (Figs. 20, 21; Fig. S4 [footnote 1]). The Eocene section is roughly 800–1000 m thick in boreholes on the shelf (Table 6) and thins significantly basinward across a broad slope ramp to 70–120 m in shallow coreholes located near the top of the escarpment (Mitchum, 1978).

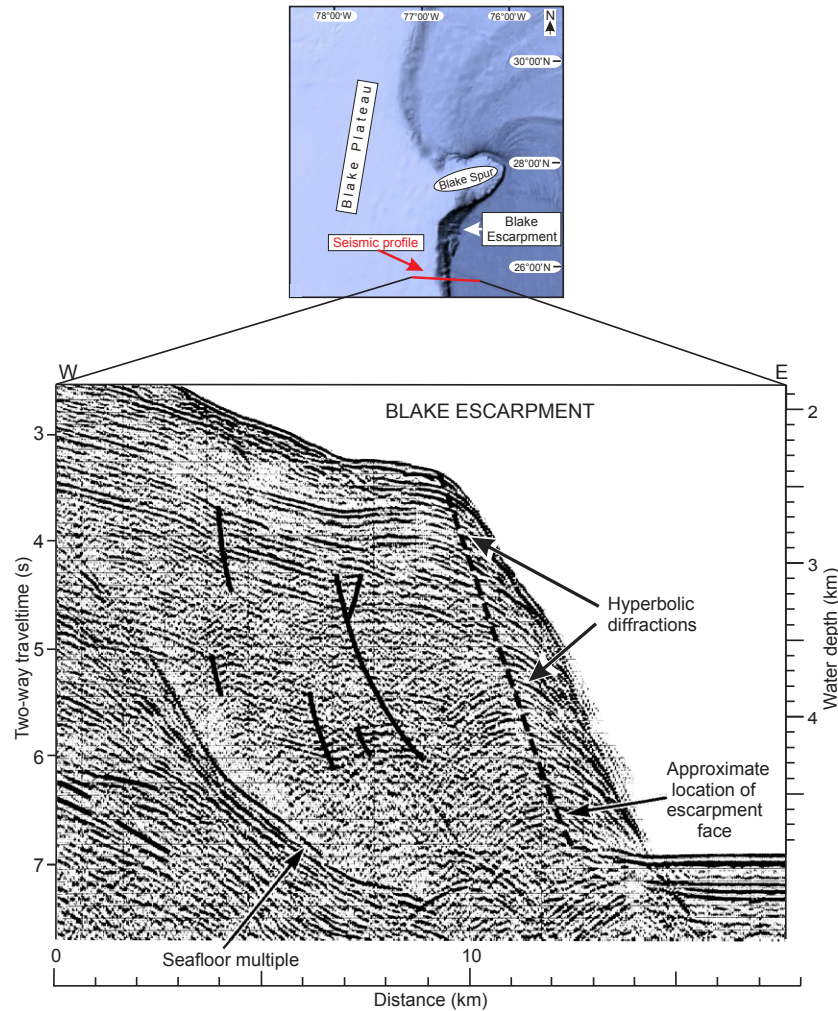


Figure 14. Seismic reflection line across the Blake Escarpment, east of the Florida Platform, shows hyperbolic diffractions that obscure the escarpment face and disrupt reflections from strata within the platform. Crests of hyperbolic diffractions approximate the true location of the escarpment face. Modified from Dillon et al. (1988); vertical exaggeration is ~4:1 at seafloor.

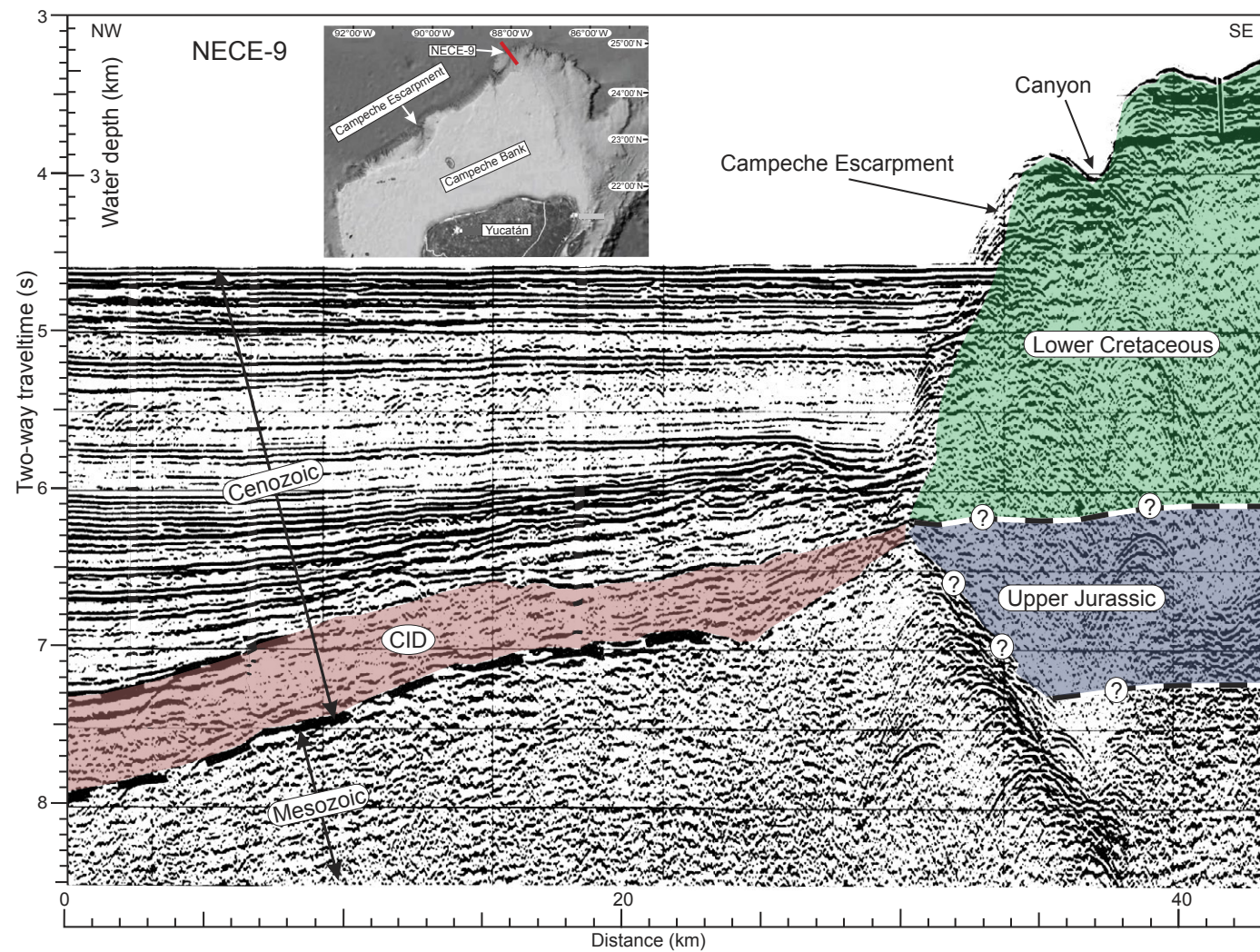


Figure 15. Portion of unmigrated seismic reflection line NECE-9 (modified from Locker and Buffler, 1983) shows the Chicxulub impact deposit (CID) abutting the north-western margin of the Campeche Escarpment. Vertical exaggeration is ~8:1 at seafloor.

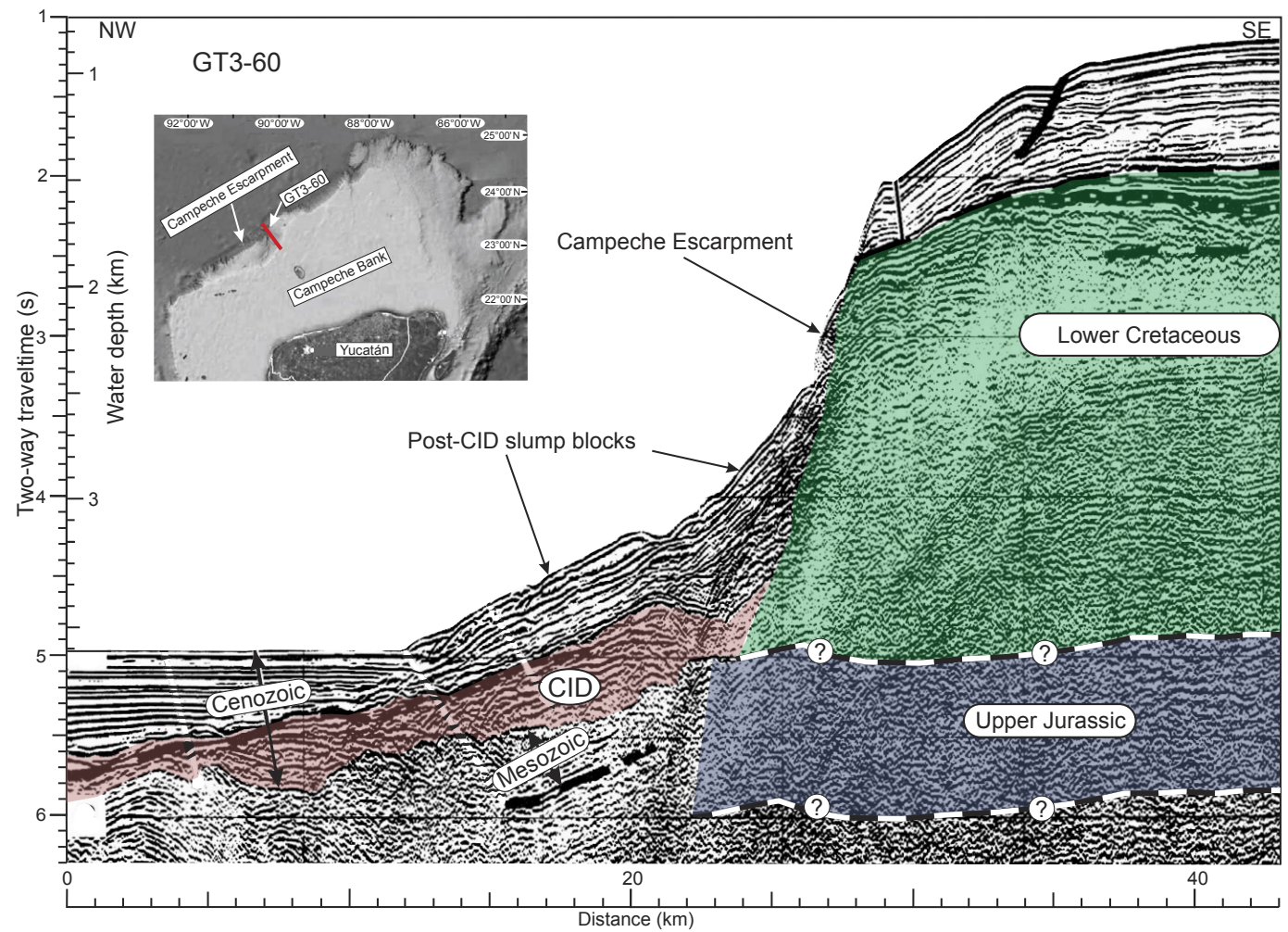


Figure 16. Portion of unmigrated seismic reflection line GT3-60 (modified from Locker and Buffer, 1983) shows the Chicxulub impact deposit (CID) overlain by large slump blocks abutting the northwestern margin of the Campeche Escarpment. Vertical exaggeration is ~8:1 at seafloor.

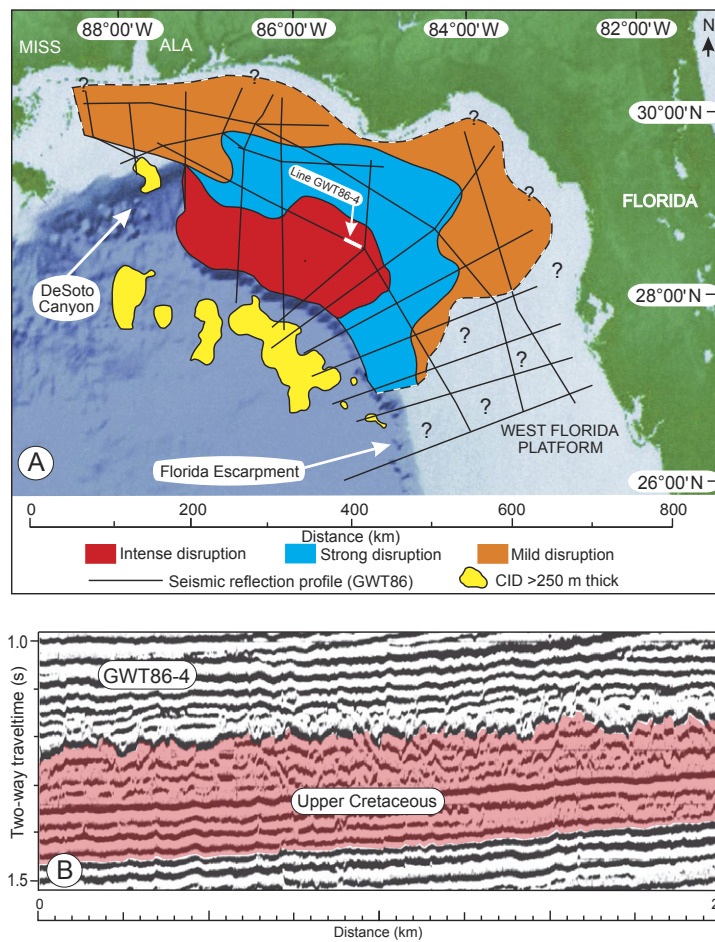


Figure 17. (A) Map of the study area shows the documented extent of sediment disruption across the West Florida Platform initiated by the Chicxulub bolide impact (after Poag, 2017). Chicxulub impact deposit (CID) distribution and thickness are from Sanford et al. (2016). MISS—Mississippi; ALA—Alabama. (B) A 20 km segment at the southeastern end of seismic reflection line GWT86-4 (strike line; see Fig. 3 for location) shows intense impact disruption in the top layers of Upper Cretaceous strata in the area indicated by the white rectangle in A.

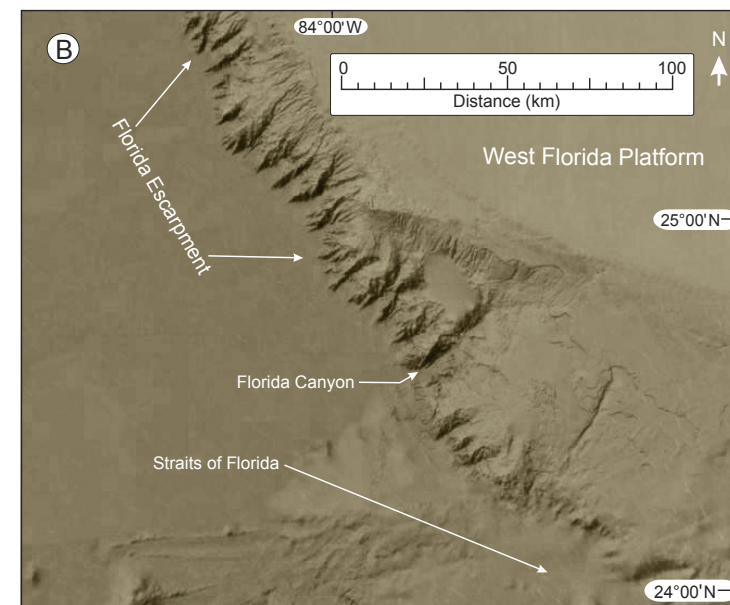
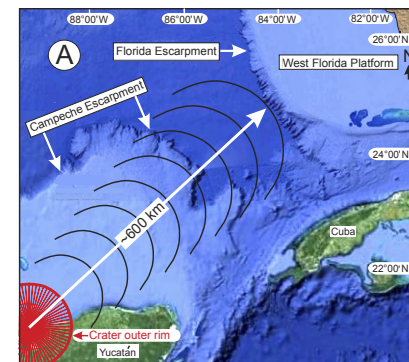


Figure 18. (A) Bathymetric shaded-relief map of the study area, the Campeche Platform and Escarpment, and the Yucatán Peninsula (Mexico) shows the proximity of the Chicxulub impact site to the heavily disrupted southeastern portion of the Florida Escarpment. (B) Enlargement of the southeastern segment of the Florida Escarpment illustrates extensive canyon and gully erosion. Bathymetry is from Google Earth.

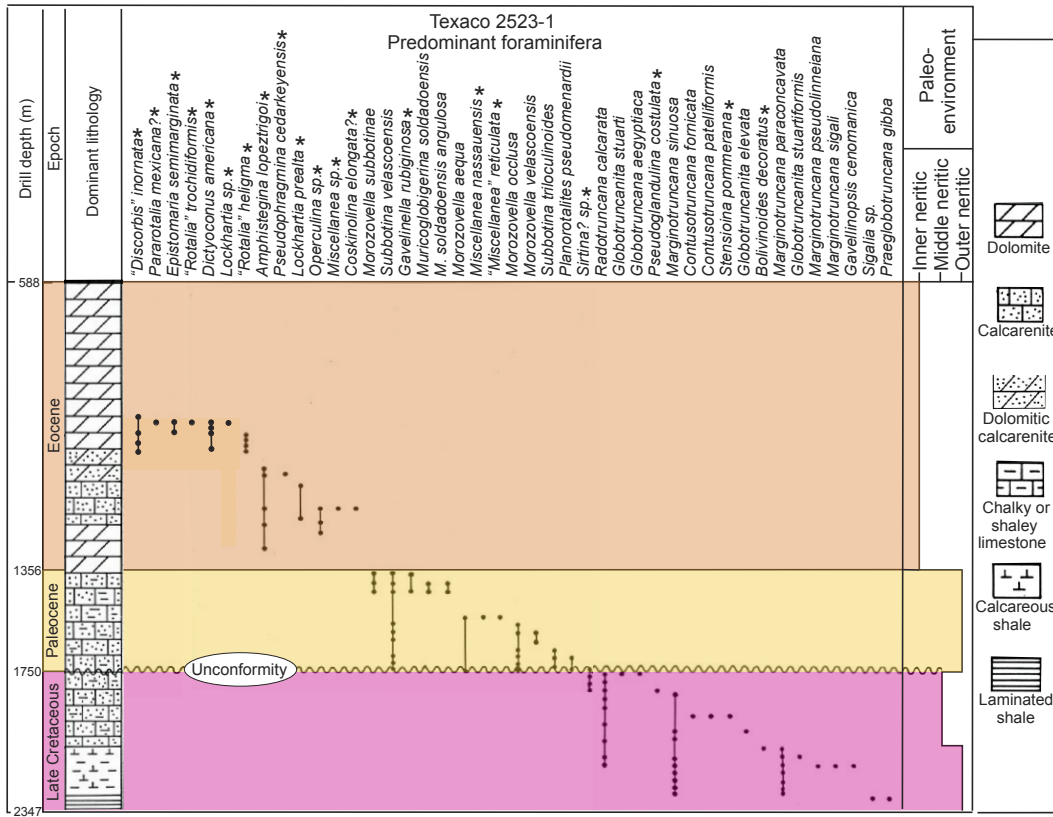


Figure 19. Biostratigraphic chart shows the dominance of inner-neritic benthic foraminifera on the Eocene shelf portion of the West Florida Platform, as documented in samples from the Texaco 2523-1 borehole (see Fig. 3 for location). Asterisk indicates benthic foraminifera; others are planktonic.

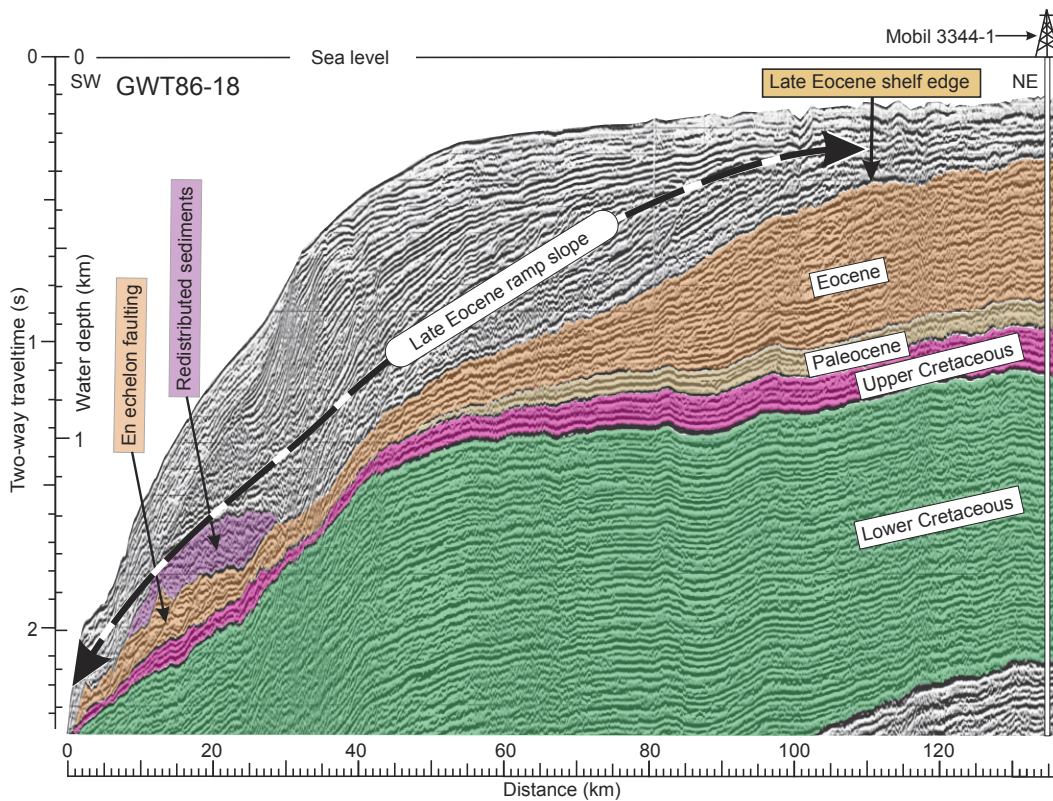


Figure 20. Laterally compressed (vertical exaggeration ~53:1 at seafloor) portion of seismic reflection line GWT86-18 (see Fig. 3 for location) shows location of Eocene shelf edge >100 km updip of ramp-slope outer edge. See Figure 23 for a less-exaggerated version (vertical exaggeration 15:1) of the outer 40 km of this line; see Figure S4 (text footnote 1) for the outer 200 km.

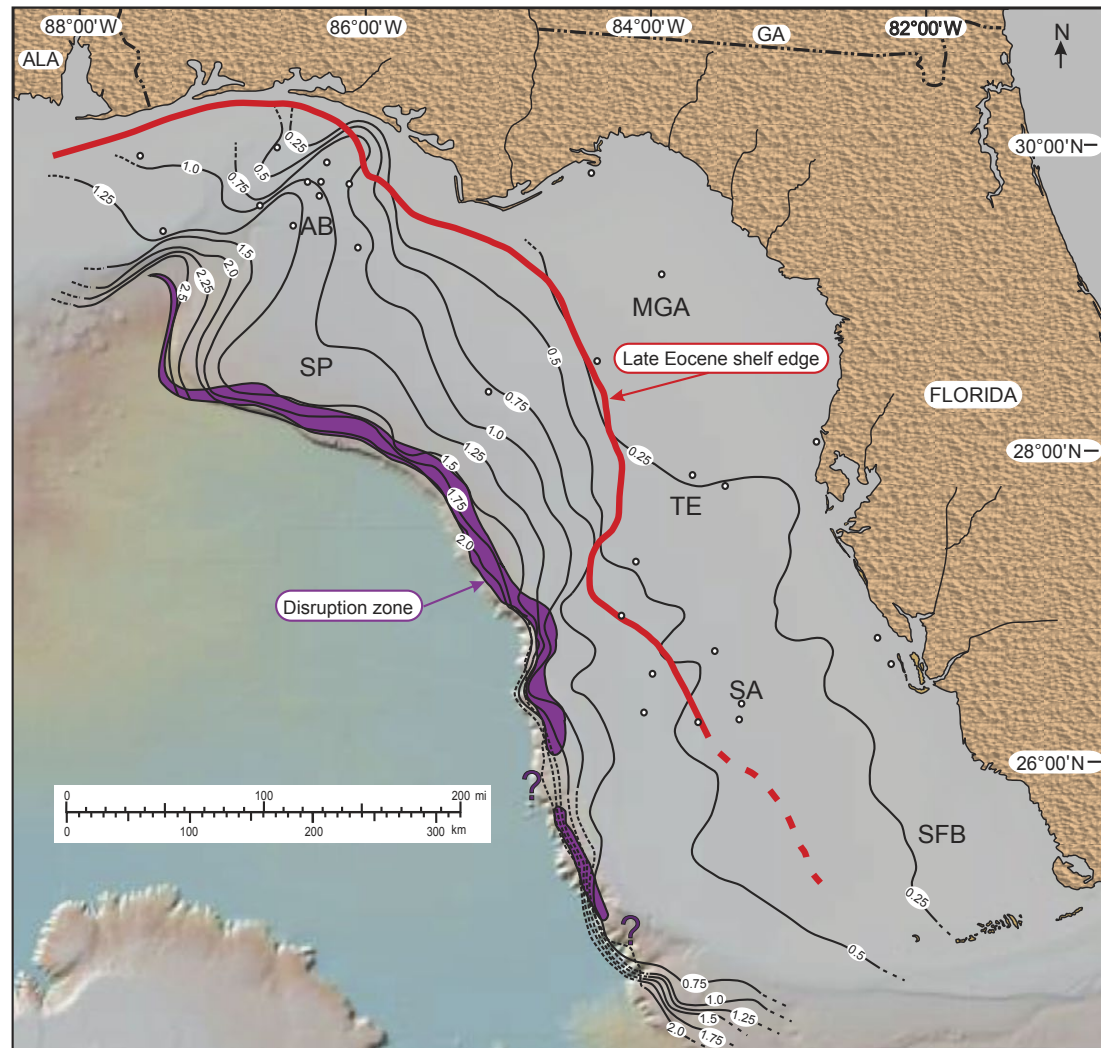


Figure 21. Structure map of the top of the Eocene unit shows (1) a broad, gently sloping shelf versus a more steeply sloping ramp slope; (2) the position of the shelf edge (red line); and (3) the location of strata disrupted and redistributed as a result of the Chesapeake Bay bolide impact (purple wedge). Structure contour interval is 0.25 s two-way traveltimes. ALA—Alabama; GA—Georgia; AB—Apalachicola Basin; SP—Southern Platform; MGA—Middle Ground Arch; TE—Tampa Embayment; SA—Sarasota Arch; SFB—South Florida Basin.

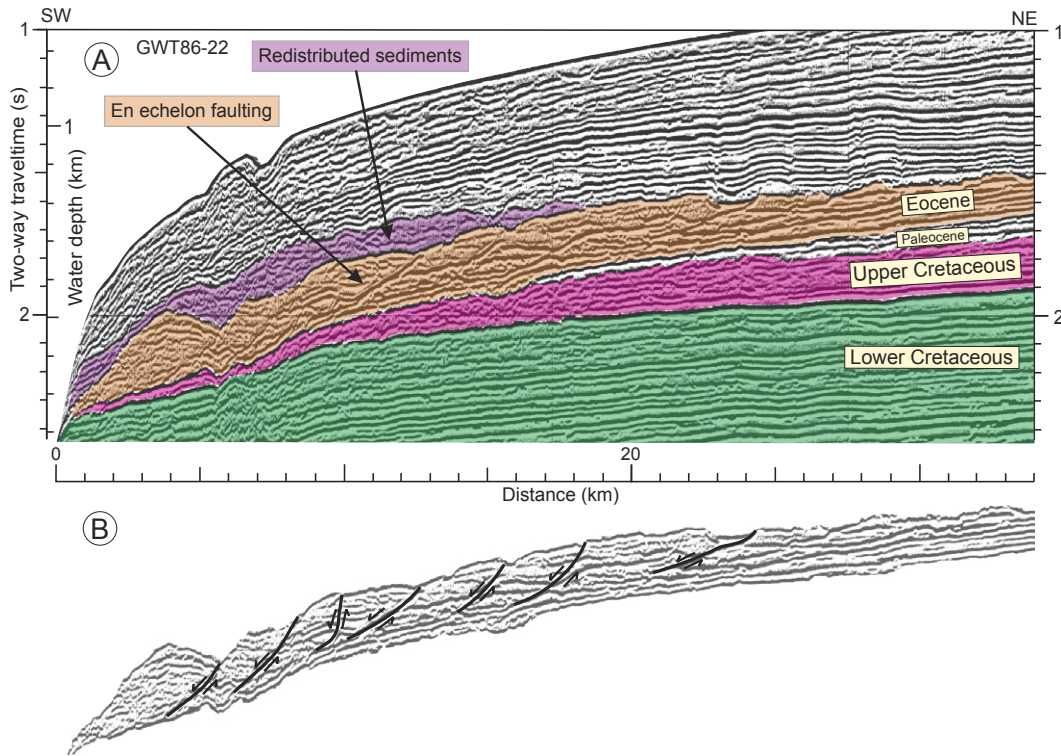


Figure 22. (A) Platform-edge segment of seismic reflection profile GWT86-22 (see Fig. 3 for location) shows a 25-km-wide zone of Eocene strata with an interval of en echelon faulting overlain by redistributed strata, both of which resulted from the late Eocene Chesapeake Bay bolide impact. (B) Interpretation of principal en echelon faults. Vertical exaggeration is 15:1 at seafloor.

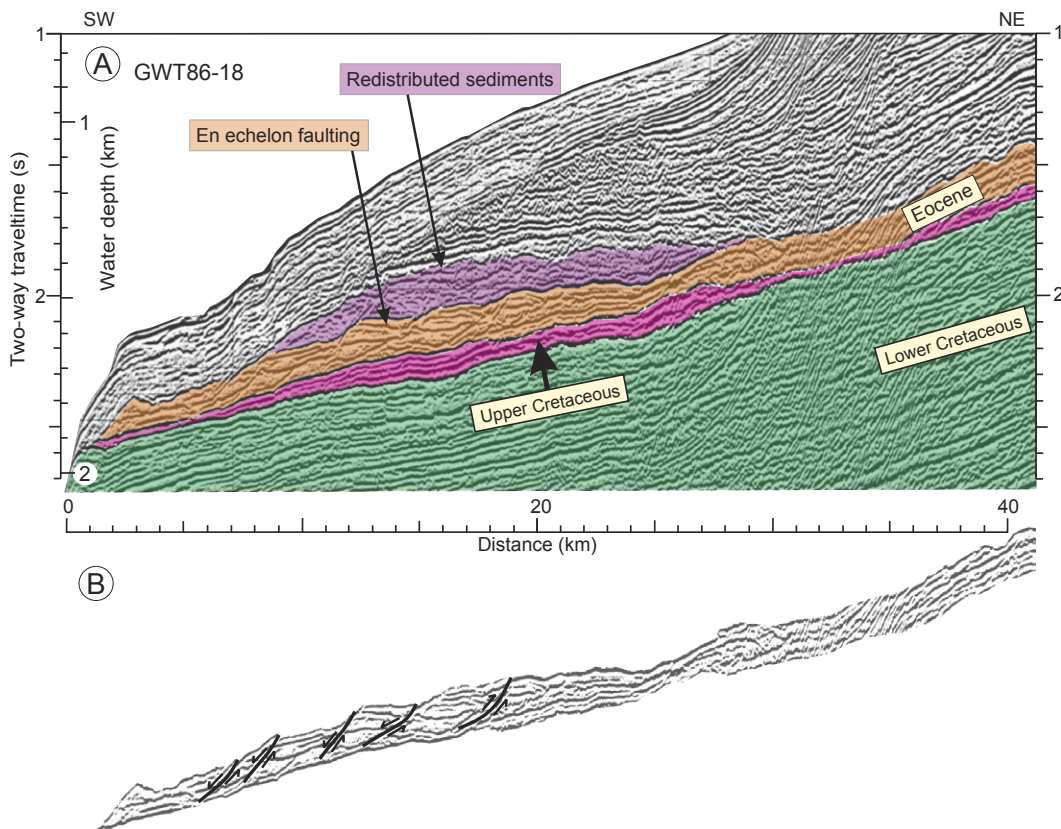


Figure 23. (A) Platform-edge segment of seismic reflection profile GWT86-18 (see Fig. 3 for location) shows a 24-km-wide zone of en echelon-faulted Eocene strata overlain by mounded, redistributed strata, both of which resulted from the late Eocene Chesapeake Bay bolide impact. (B) Interpretation of principal en echelon faults. Vertical exaggeration is 15:1 at seafloor.

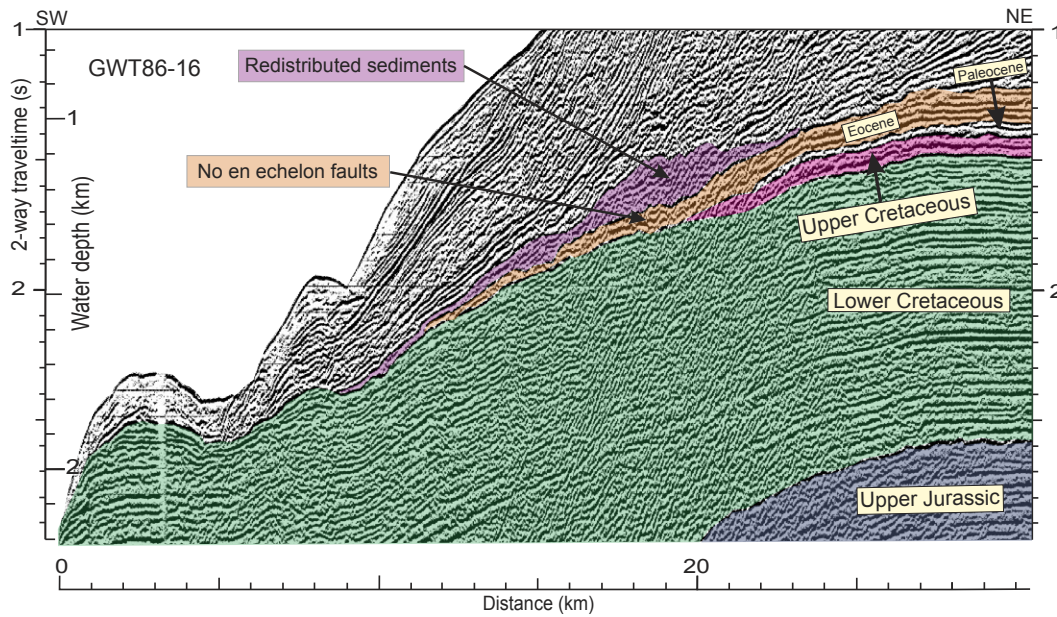


Figure 24. Platform-edge segment of seismic reflection profile GWT86-16 (see Fig. 3 for location) shows a ~15-km-wide zone of redistributed strata, which resulted from the late Eocene Chesapeake Bay bolide impact, and no obvious en echelon faulting in the underlying layer. Vertical exaggeration is 11:1 at seafloor.

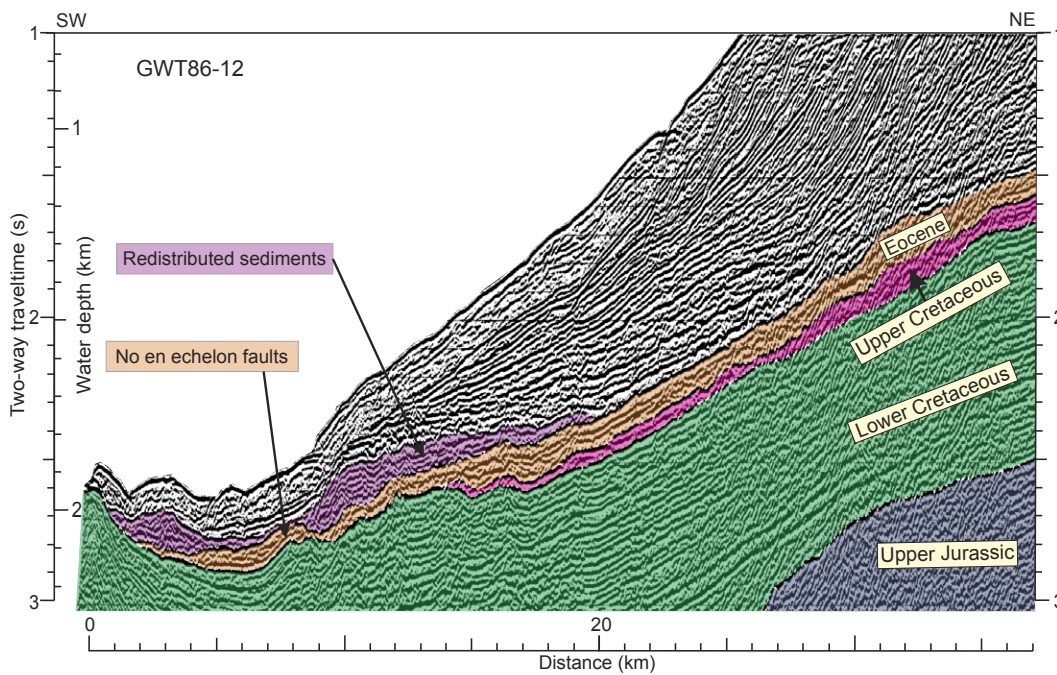


Figure 25. Platform-edge segment of seismic reflection profile GWT86-12 (see Fig. 3 for location) shows a ~20-km-wide zone of redistributed strata, which resulted from the late Eocene Chesapeake Bay bolide impact, and no obvious en echelon faulting in the underlying layer. Vertical exaggeration is 11:1 at seafloor.

A notable characteristic of the upper Eocene section on the West Florida Platform is a relatively narrow zone (~11–28 km wide) of faulted and/or mounded sediments that extends for ~270 km along the upper edge of the Florida Escarpment (Figs. 21–25). Randazzo (1997) illustrated this disrupted unit along a seismic reflection profile that approximates profile GWT86-19. In the context of the Lower Cretaceous shelf, this might be explained as a reef-rimmed margin. However, the pelagic water depths this far basinward from the Eocene shelf edge would have been too deep for reef development.

The seismic data indicate that most of the mounded zone contains two distinct types of disrupted strata. Where both types are present, the lower layer displays high-amplitude, continuous reflections, broken up into distinctive en echelon block faults (Figs. 22, 23; Figs. S5–S9 [footnote 1]). In contrast, the upper layer displays low-amplitude, discontinuous, chaotic reflections (folds, fractures, slumps, faults) similar to those typical of the disrupted Upper Cretaceous strata of the West Florida Platform (Fig. 17; Poag, 2017). I interpret this bipartite arrangement to indicate in situ disruption of the lower, high-amplitude layer resulting from seismic shaking and ground roll, whereas the upper chaotic layer probably represents debris displaced from updip locations via debris flows, slumps, and slides. This material would have been redistributed from the late Eocene shelf or upper ramp slope as a result of tsunami-driven currents arising from a marine impact. A few sites clearly exhibit the upper layer of redistributed debris (Figs. 24, 25) but with no obvious en echelon faulting in the lower layer.

I infer that the late Eocene Chesapeake Bay impact (Poag et al., 2004), ~1300 km northeast of the Florida Escarpment (Fig. 26), provided the kinetic energy for this two-stage disruption. Applying an impactor size of ~3 km diameter (Collins and Wünnemann, 2005), the online numerical model of Melosh et al. (2004) predicts that the impactor entered the atmosphere at a velocity of ~17 km/s imparting a kinetic energy burst of $\sim 2 \times 10^6$ Mt TNT to the seafloor. Major seismic shaking (Richter scale magnitude ~9) traveled from the Chesapeake Bay impact site to the Florida Escarpment within ~4 min after impact. These approximate predictions would vary depending on the precise size, velocity, and approach angle of the impactor, which are not known at present. The subsequent tsunami would have reached the Florida Escarpment ~2 h after impact. A direct oceanic connection existed between the impact site and the West Florida Platform because the Florida peninsula was submerged during the Eocene (Fig. 26).

SUMMARY AND CONCLUSIONS

Widespread evidence of individual bolide impacts usually is limited to the airborne spread of small ejecta particles, such as microtektites, or an unusual abundance of cosmic elements, such as iridium. An iridium spike and associated ejecta derived from the Chicxulub impact are globally well documented (e.g., Smit, 1999; Goderis et al., 2013). The most thoroughly documented far-field effect from the Chesapeake Bay impact is a broad field of microtektites and associated ejecta (North American tektite strewn field), recognized mainly in the Atlantic Ocean and U.S. Coastal Plain (e.g., Koeberl et al., 1996; Glass et al., 1998; Biren et al., 2019).

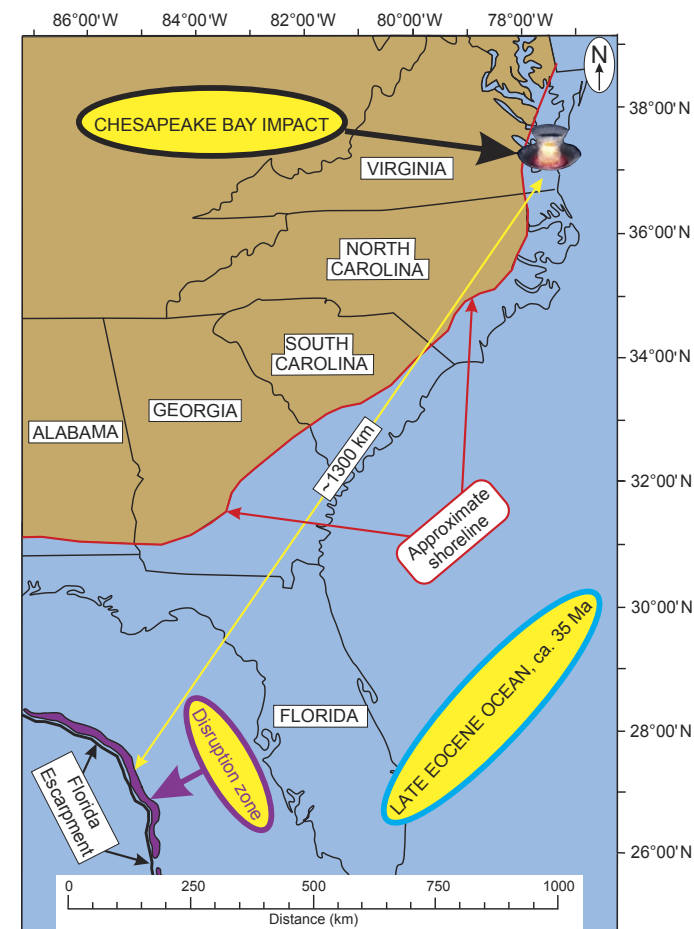


Figure 26. Paleogeographic map of the southeastern United States shows the late Eocene (ca. 35 Ma) shoreline and distance between the Chesapeake Bay impact in Virginia and the impact-related disruption zone on the West Florida Platform. Shoreline position is from Deep Time Maps (<https://deeptimemaps.com/>).

The ages and origins of ejecta deposits can be verified by objective geochemical and mineralogical methods, whereas recognition of seismic and tsunami effects depends more on subjective observational interpretation of field data. The extensive database collected from industry and academic seismic surveys in the Gulf of Mexico provides a unique opportunity to observe the detailed stratigraphic and depositional history of this region. As a result, disruptive seismic effects from the Chicxulub impact have been most firmly

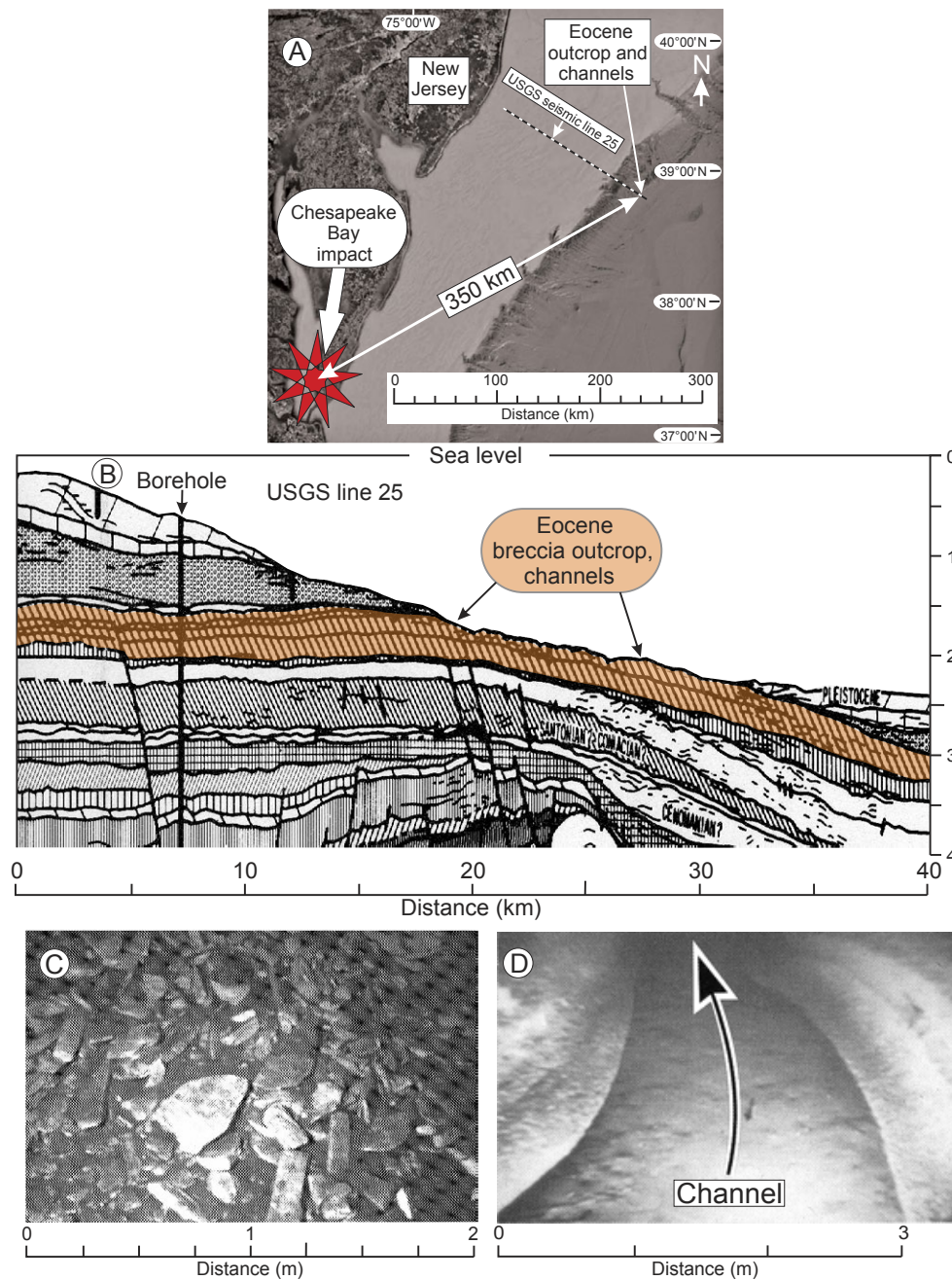


Figure 27. Effects from the Chesapeake Bay bolide impact on the U.S. Atlantic margin. (A) Bathymetric map of the seafloor northeast of Chesapeake Bay (offshore Virginia) shows the location of a lower and middle Eocene outcrop containing brecciated limestone and unusual seafloor channels attributed to seismic and tsunami effects of the Chesapeake Bay bolide impact. **(B)** Stratigraphic interpretation of U.S. Geological Survey (USGS) seismic reflection line 25 (see map above for location) shows a ~14-km-wide outcrop of Eocene brecciated limestone and the location of unusual channels on the lower continental slope off New Jersey (modified from Poag, 1985). **(C)** Seafloor photograph shows angular clasts in a talus apron derived from a cliff-face outcrop of brecciated middle and lower Eocene limestone. **(D)** Seafloor photograph shows an unusual near-vertical-walled channel in an Eocene limestone outcrop (seafloor photos from Poag et al., 2004).

documented in the Gulf of Mexico (e.g., Locker and Buffler, 1983; Corso et al., 1988; Grajales-Nishimura et al., 2000; Paull et al., 2014; Sanford et al., 2016; Poag, 2017). Related studies outside the Gulf of Mexico include the Caribbean region (e.g., Bralower et al., 1998; Tada et al., 2003), the western North Atlantic (e.g., Klaus et al., 2000; Norris et al., 2000), and the Adriatic region (Korbar et al., 2015). The data presented herein from the West Florida Platform support previous interpretations that the Chicxulub bolide impact produced instantaneous widespread platform-margin collapse, resulting in a significant shoreward retreat of the Florida Escarpment. The resultant sedimentary debris collected as a continuous apron along the base of the escarpment. My interpretation recognizes this debris as the Chicxulub impact deposit, which is not a transitional unit between the Cretaceous and Paleogene Periods but accumulated entirely in the first few days of the Paleocene Epoch (Danian Age).

Only a single previous report of wide-field physical disruption from the Chesapeake Bay bolide has been published. Poag et al. (2004) reported initial recognition of possible seismic and tsunami effects from the Chesapeake Bay impact based on observations from submersible dives on the lower continental slope of New Jersey, ~350 km northeast of the impact site. A broad, linear, cliff-faceted outcrop (>10–15 km wide) of highly fractured and brecciated lower and middle Eocene pelagic limestone occupies that location (Figs. 27A–27C). The same area features unusual vertical-walled, flat-bottomed erosional channels (3–5 m wide, 4–13 m deep) with axes trending downslope (Robb et al., 1983; Figs. 27A, 27B, 27D). I interpret these features to represent another example of fracturing and brecciation due to seismic shaking and ground roll followed by unusual channeling created by tsunami-generated bottom currents, a two-step disruption similar to the end-Cretaceous and late Eocene disruption phases indicated on the West Florida Platform.

Among the approximately dozen known submarine craters (Poag et al., 2004), far-field seismic effects have been reported from only two—Chicxulub and Chesapeake Bay. Though many published reports have noted such effects attributable to the Chicxulub impact, this is only the second report of such effects derived from the Chesapeake Bay impact. It is the first report of their recognition in the Gulf of Mexico.

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