GCAGS JOURNAL
A Publication of the
Gulf Coast Association of
Geological Societies
www.gcags.org

Impact on Sedimentation into the North-Central Deepwater Gulf of Mexico as a Result of the Chicxulub Event

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ABSTRACT

The Chicxulub bolide impact on the Yucatan Peninsula at the Cretaceous-Paleogene (K/Pg) boundary has been postulated as the trigger that re-mobilized large quantities of sediment into mass transport flows on the submerged shelf along eastern North and Central America, as well as around the Gulf of Mexico, and redistributed sediment out into the deepwater Atlantic, Caribbean, and Gulf of Mexico. Well log and biostratigraphic data from Cretaceous well penetrations in the north-central deepwater Gulf of Mexico show a distinctive calcareous micrite deposit at the K/Pg boundary that is similar in composition to age-equivalent sediments found near the Chicxulub Crater, in Deep Sea Drilling Program (DSDP)/Ocean Drilling Program (ODP) cores, and in outcrops in Cuba. Investigation of seismic volumes in the north-central Gulf of Mexico shows distinctive sedimentary wedges that exhibit high-amplitude reflections situated at the top of the section interpreted as Cretaceous. This interval is thought to be the resulting deposit from the mass transport flows and suspension fallout initiated by the impact. As the Chicxulub impact occurred, the north-central Gulf of Mexico was undergoing allochthonous salt movement from the Jurassic Louann Salt that included numerous salt highs shaping potential clastic sediment fairways. Sediment redistribution caused by the Chicxulub impact from the shelf and slope to the deepwater environment filled in available accommodation space around salt highs, as well as deposited sediments on the highs themselves, and altered the seafloor topography across the north-central Gulf of Mexico.

SEDIMENT REWORKING AROUND NORTH AND CENTRAL AMERICA

The Chicxulub impact is estimated to have caused a magnitude 11 earthquake and tsunamis 300–1000 ft (100–300 m) in height and spread ejecta material around the globe (Schulte et al., 2010). Reviewing known K/Pg boundary data locations, Schulte et al. (2010) classified sites around the northwestern Gulf of Mexico as proximal to the impact site that are characterized by cm- to m-thick ejecta spherule-rich and clastic event beds indicative of high-energy sediment transport processes. Tsunami and mass wasting deposits (e.g., chaotic sediments, breccias, coarse clastic units, debris flows, and tsunamites) have been recognized around the Gulf of Mexico (Claeys et al., 2002). Along the Atlantic margin of North America, Deep Sea Drilling Program (DSDP)/Ocean Drilling Program (ODP) drill sites and seismic evidence show extensive K/Pg boundary slope failure deposits (Norris and Firth, 2002).

Of the outcrops around the Gulf of Mexico identified as containing the K/Pg boundary, only sections in Cuba have been interpreted to be deposited in similar water depths, middle to lower bathyal depths of the proto-Caribbean Sea, and slope and basin environments as the current study area in the north-central Gulf of Mexico that were subsequently scraped onto the island as it moved northward to its current position (Alegret et al., 2005). The Moncada Formation is a thin (~6.5 ft [2 m]) upward-fining calcareous grainstone (calcarenite) deposited on the paleo-slope (Goto et al., 2008; Tada et al., 2003), while the much thicker Cacarajicara Formation (up to 2300 ft [700 m]) and portions of the Peñalver Formation (up to 600 ft [180 m]) were deposited in a basinal setting (Fig. 1). The Cacarajicara and Peñalver formations are comprised of a basal carbonate breccia up to 900 ft (275 m), and a middle member of an upward-grading massive to well-bedded homogenous calcareous grainstone (calcarenite) that grades into upper and uppermost members consisting of a fine-

Manuscript received March 24, 2014; revised manuscript received July 3, 2014; manuscript accepted July 3, 2014.

GCAGS Journal, v. 3 (2014), p. 41–50.

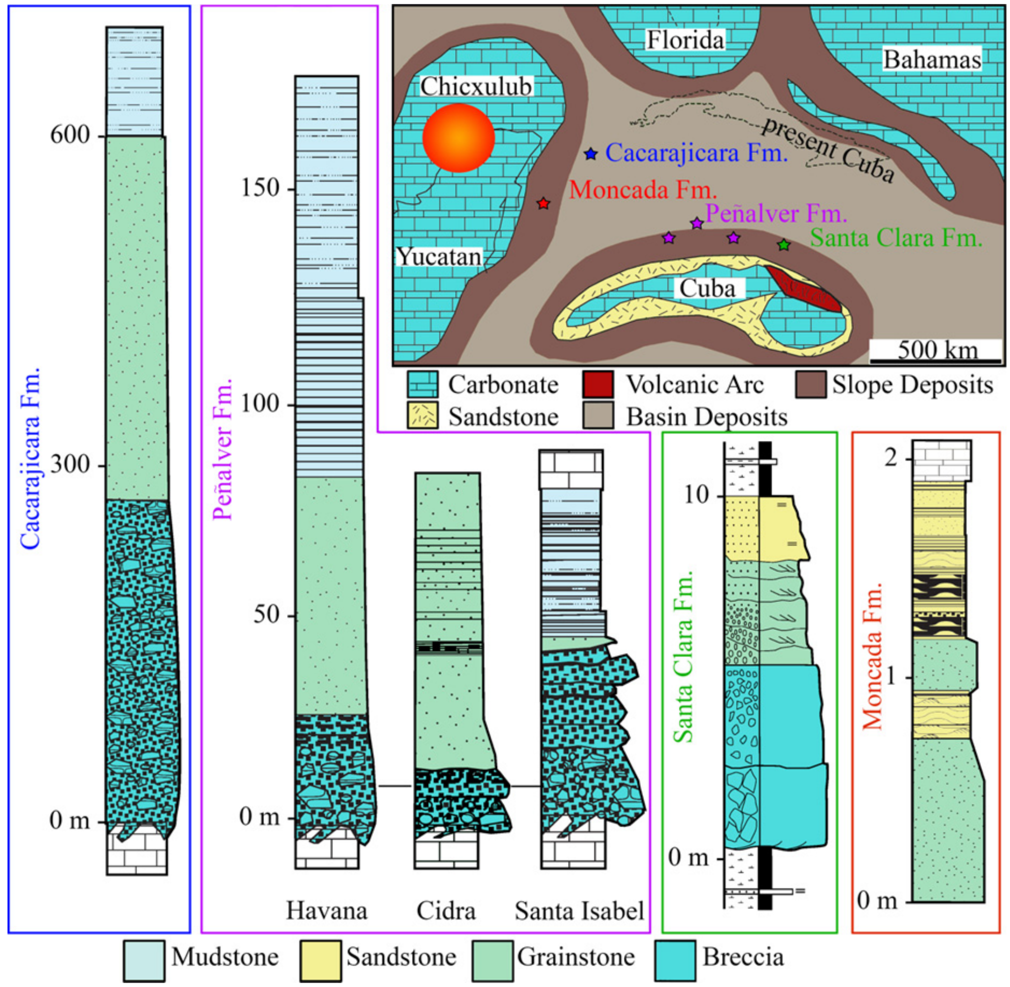


Figure 1. Measured sections from outcrops of the Cacarajicara, Peñalver, Santa Clara, and Moncada formations in Cuba showing the Chicxulub impact stratigraphy deposited on slope to basin settings (modified after Goto et al., 2008; Tada et al., 2003; Alegret et al., 2005). Note that all of the sections exhibit a fining-upward sequence. Sections are displayed at different scales.

grained calcarenite to calcareous mudstone (calcilutite) that shows no discernible break in deposition or signs of bioturbation (Kiyokawa et al., 2004). The basal member is interpreted to have been formed under high-density flow conditions with the middle member probably deposited from a high-density turbidity flow, while the upper and uppermost members were deposited from dilute, low-density turbidity flow (Kiyokawa et al., 2004). In the Santa Clara Formation, a 31.5 ft (9.6 m) sequence (Fig. 1) has similar fining-upward characteristics and pattern as the Cacarajicara and Peñalver formations (Alegret et al., 2005). All of these sequences are interpreted as being deposited in a deepwater setting (>1000 ft [>300 m]) and display a consistent fining upward pattern across varying vertical thicknesses that are interpreted to represent deposition from a single sediment gravity flow event initiated by earthquakes and by tsunami waves created by the Chicxulub impact and the subsequent collapse of the Campeche carbonate platform (Goto et al., 2008; Alegret et al., 2005; Kiyokawa et al., 2002, 2004; Tada et al., 2003).

SEDIMENT REDISTRIBUTION INTO THE DEEP WATERS OF THE GULF OF MEXICO

Redistribution of sediments caused by the earthquake and tsunami from the Chicxulub impact is well documented from outcrops around the Gulf of Mexico as well as offshore in DSDP/ODP cores and seismic data from the Gulf of Mexico and Atlantic margin with many of these papers suggesting debris flows/mass wasting/mass transport deposits present in deepwater areas of the Gulf of Mexico (e.g., Goto et al., 2008; Norris and Firth, 2002; Claeys et al., 2002; Bralower et al., 1998). Recent industry activity in the north-central deepwater Gulf of Mexico has provided new data to assess the extent of the redistribution of sediments from the shelf and slope into the deep basin and guidance on the possible sedimentary processes involved.

Well Control

Thirty-two wells drilled by industry in the north-central deepwater (>1000 ft [>300 m]) Gulf of Mexico as of 2013 are known to have penetrated the K/Pg boundary (Fig. 2). In 17 of these wells, a sedimentary unit was identified immediately below the K/Pg boundary that contained a unique assemblage of biostratigraphic markers (Denne et al., 2013) similar to a layer found at the southern Gulf of Mexico DSDP sites 536, 540, and 1001. The layer in the DSDP cores was characterized by microfossils of mixed Cretaceous age attributed to be the result of sediment mixing initiated by the Chicxulub impact (Bralower et al., 1998). Thicknesses of this K/Pg boundary unit in these wells, most with only partial penetrations, range from over 650 ft (200 m) in the western Gulf of Mexico to less than 65 ft (20 m) in the east. Three industry wells drilled full sections of this unit and show the character of the K/Pg boundary deposit in the north-central deepwater Gulf of Mexico (Fig. 3). The Alaminos Canyon 557 #1BP2 well (Baha II prospect) penetrated 2244 ft (684 m) of Cretaceous section, composed of a 669 ft (204 m) thick massive, micritic limestone sitting on 1575 ft (480 m) of interbedded calcareous shales and limestones. The upper limestone contains the mixed microfossil assemblage related to the Chicxulub impact and is defined on well logs by a sharp deflection at ~5362 ft (1634 m) measured depth to a lower gamma-ray reading that remains consistently low throughout the unit. Also at ~5362 ft (1634 m) measured depth, the resistivity response of the unit

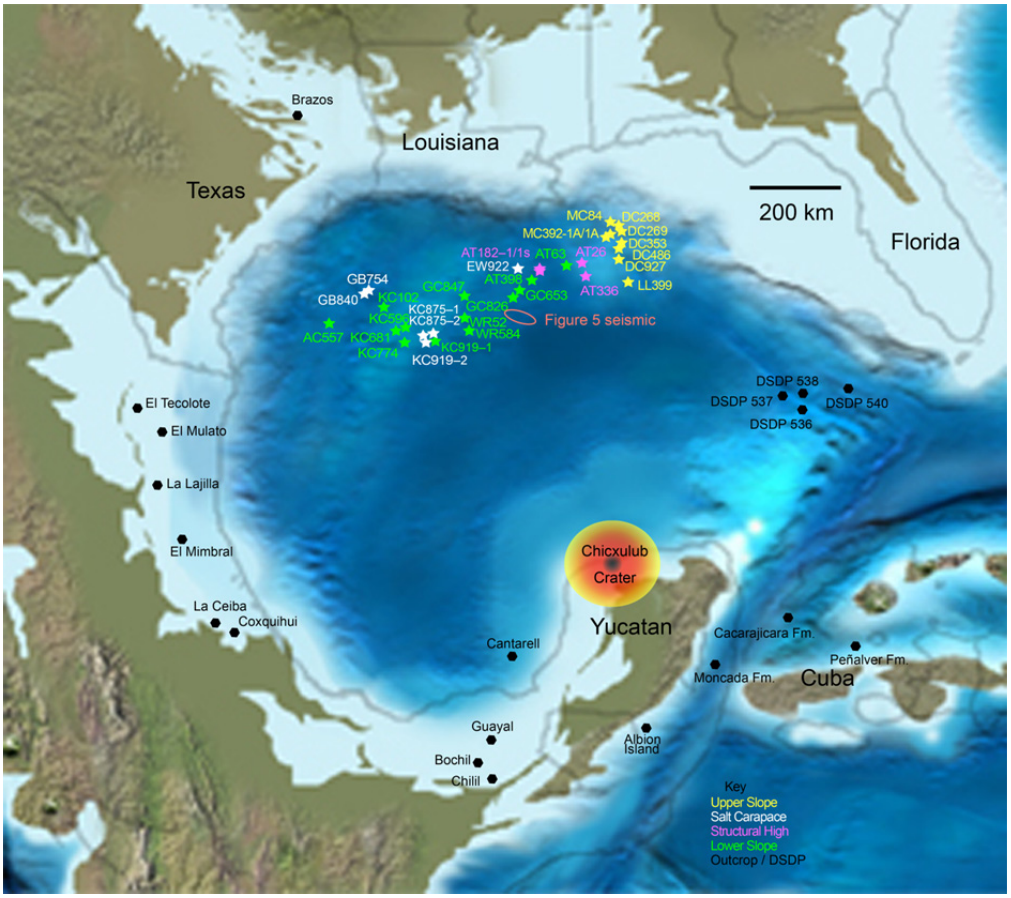


Figure 2. Locations of wells penetrating the K/Pg boundary in the north-central deepwater Gulf of Mexico in relation to the Chicxulub crater. The color of the well symbols relates to the interpreted position on the continental slope at the time of the impact. Pink wells were on a paleo structural high and hold no impact related deposits. Yellow wells were in the upper slope and hold impact related deposits from 32–220 ft (10–67 m). Green wells are from a lower slope setting and hold incomplete penetrations of 50–213 ft (15–65 m) of impact related deposits and complete penetrations from 295–670 ft (90–204 m). White wells had impact related deposits from 50–280 ft (15–85 m) that are interpreted to have been situated on bathymetric highs related to salt movement (carapace). Outcrop and DSDP localities with K/Pg boundary deposits around the Gulf of Mexico are shown in black. The background map is the 65 Ma North American paleogeography from Blakey (2011).

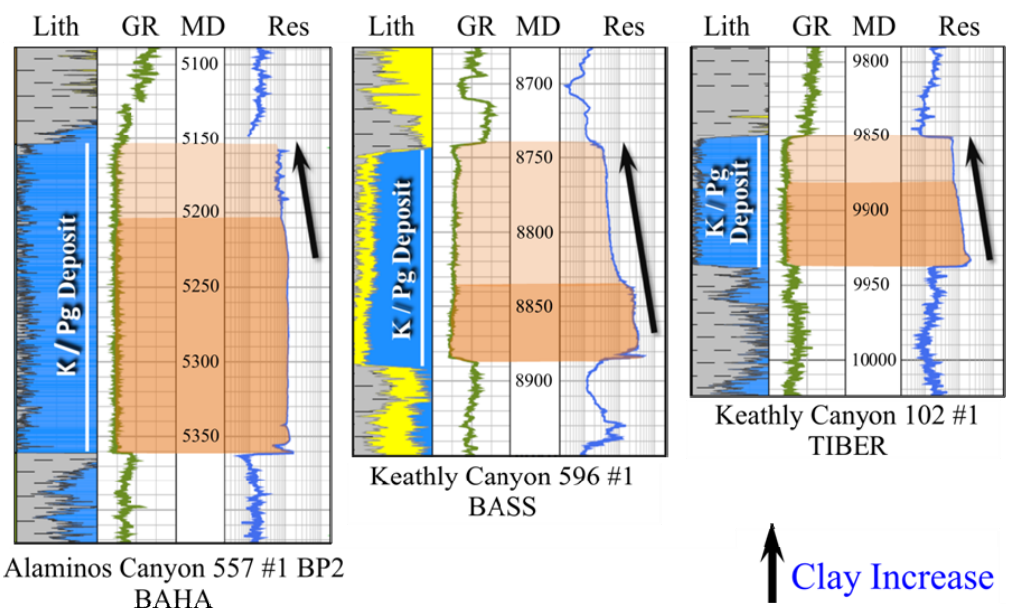


Figure 3. Well data from Alaminos Canyon 557 #1, Keathley Canyon 596 #1, and Green Canyon 653 #3 showing elements of the Chicxulub impact deposit stratigraphy similar to what is seen in the Cuban outcrops. Log depths in feet. Lith = Lithology, GR = Gamma Ray, MD = Measured Depth, and Res = Resistivity.

shows a similar sharp deflection to a higher resistivity spike then maintains a high value to a measured depth of ~5205 ft (1586 m), where resistivity slowly reduces, attributed to an increase in clay content, to the top of the unit that is defined by a sharp transition to a low resistivity. A similar, mixed microfossil unit in the Keathley Canyon 596 #1 well (Bass prospect) has a gamma-ray response comparable to Alaminos Canyon 557 #1BP2 with a sharp base and top. The resistivity log also contains a similar reading with a sharp positive spike at the base of the section, maintaining a high resistivity value in the lower portion and then slowly reducing in value in the upper section of the deposit with a quick transition to lower resistivity indicating the top of the unit. Keathley Canyon 102 #1 (Tiber prospect) shows a similar pattern to the other wells in a 99 ft (30 m) thick mixed microfossil interval, with a deflection in both gamma ray and resistivity response at approximately two thirds of the way up the thickness from the base of the unit. The other Gulf of Mexico well penetrations all show comparable low gamma ray and high resistivity readings over the interval containing the diagnostic mixed microfossil assemblage.

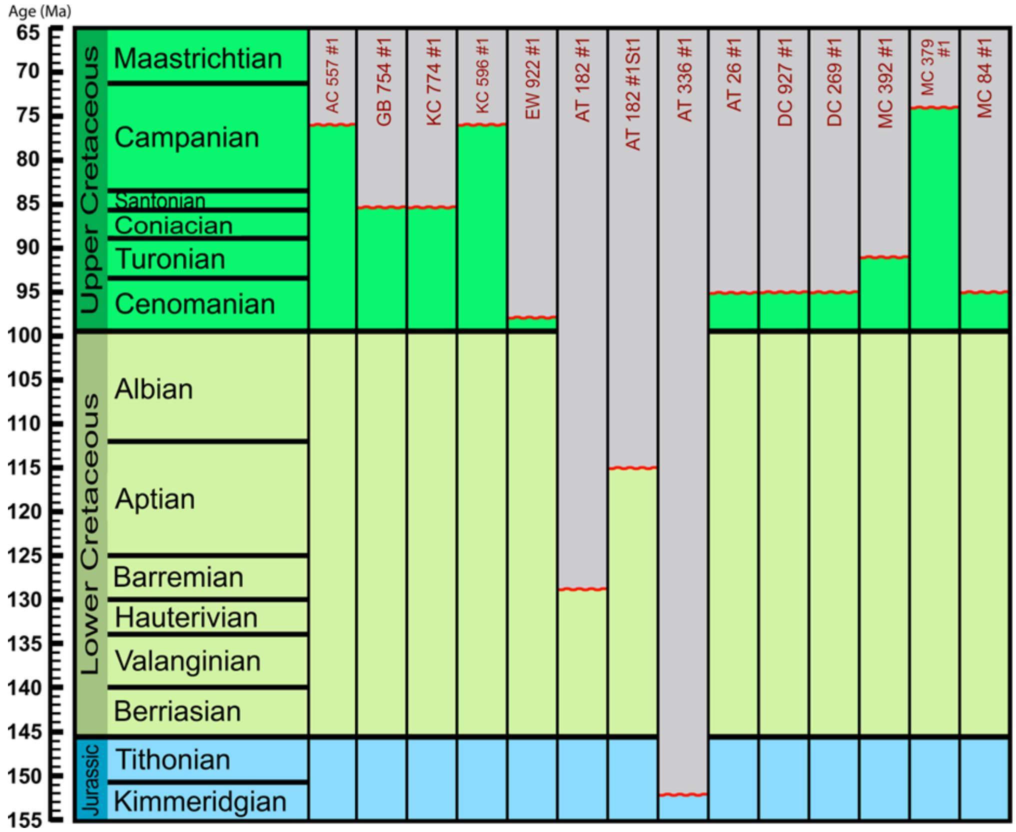


Figure 4. Amount of time represented by the erosional unconformity at the base of the impact deposit in wells from the north-central Gulf of Mexico.

Underlying the impact deposit at the biostratigraphically defined K/Pg boundary in all the wells is an unconformity that represents varying amounts of missing time, from the Maastrichtian to mid-Campanian in all the penetrations to locally into the Jurassic (Fig. 4). Overlying the impact deposit is a sedimentary unit known informally as the Midway shale (the lowest part of the Midway Group), described as a condensed section consisting of mudstone that represents sedimentation from predominately pelagic and hemi-pelagic processes (Denne, 2007; Blickwede et al., 2004; Fillon and Lawless, 1999) over the next 4.4 m.y. after the impact.

Seismic Data

The seismic reflection interval with the K/Pg deposit is identified with good- to high-quality seismic imaging (Fig. 5). This deposit has the following distinguishing characteristics: (1) An extensive high-amplitude reflector that separates two distinctive seismic facies; (2) in areas beyond the Sigsbee Escarpment, where the seismic data is not degraded by shallow salt layers, the horizon is typified by a concordant, parallel couplet of high-amplitude; (3) truncation of deeper horizons, significant thinning, and possible onlapping of younger horizons on paleo-highs, and (4) considerable thickening in paleo-lows, even when the horizons above and below the unit are relatively concordant.

Recent advances in seismic imaging now illuminate the Cretaceous section in areas with shallow salt. Seismic data from the Keathley Canyon and Walker Ridge areas in the north-central deepwater Gulf of Mexico reveals the Cretaceous interval as recognized by the criteria established in the salt free areas and confirmed by well penetrations. In this area an anomalous seismic facies of multiple high-amplitude, onlapping seismic reflections are at the top of the Cretaceous section (Figs. 6–8). This facies appears to be very distinct from the underlying low-amplitude, discontinuous seismic reflections that typify the Cretaceous sediments as well as to the overlying very low-amplitude, almost opaque seismic facies of the Paleocene/Lower Eocene section. This unique seismic facies exhibits a wedge cross section up to 2600 ft (800 m) thick, usually adjacent a deep Plio-Pleistocene minibasin that loaded into a large salt feeder (Hudec et al., 2008), with a roughly rounded or oval map pattern of 2–4 mi (3–7 km) in width and 5–9 mi (8–15 km) in length (Fig. 9). Observed onlap geometries of the seismic reflectors and characteristics of this anomalous seismic facies, along with the map patterns, imply that the sediments filled up seafloor topographic lows. Positioned between the interpreted Cretaceous and Paleogene seismic sections, these wedges of different seismic facies do not appear to be genetically associated with either the stratigraphy of the underlying Mesozoic section or with the overlying clastic-rich Paleogene Wilcox Group sediments (Galloway et al., 2011). They are interpreted to be related to the sediment redistribution caused by the Chicxulub impact.

Implications of Seismic Interpretation

The seismic wedges identified in the Keathley Canyon and Walker Ridge areas contain multiple seismic reflections indicating internal layering of the sediment package. The Cuban outcrops of the Moncada, Cacarajicara, Peñalver, and Santa Clara formations exhibit a distinctive fining-up layering pattern of the impact strata; a coarse-grained lithology was deposited at the base and transitions to very fine-grained lithologies at the top that could result in enough density contrast to create multiple seismic reflectors as is seen in the seismic wedges (Figs. 6–8). Data from well logs and limited well cuttings from penetrations of the K/Pg boundary unit in the north-central deepwater Gulf of Mexico show predominately fine- to very fine-grained, calcareous lithologies with increasing mud content upwards placing the strata encountered in the wells in the upper portion of the full impact event stratigraphy observed in the Cuban outcrops, perhaps equivalent to the pattern seen in the Moncada Formation. This layering of varying rock properties in the impact strata in the north-central deepwater Gulf of Mexico is indicated in the logs from the Keathley Canyon 596 #1, Keathley Canyon 102 #1, and

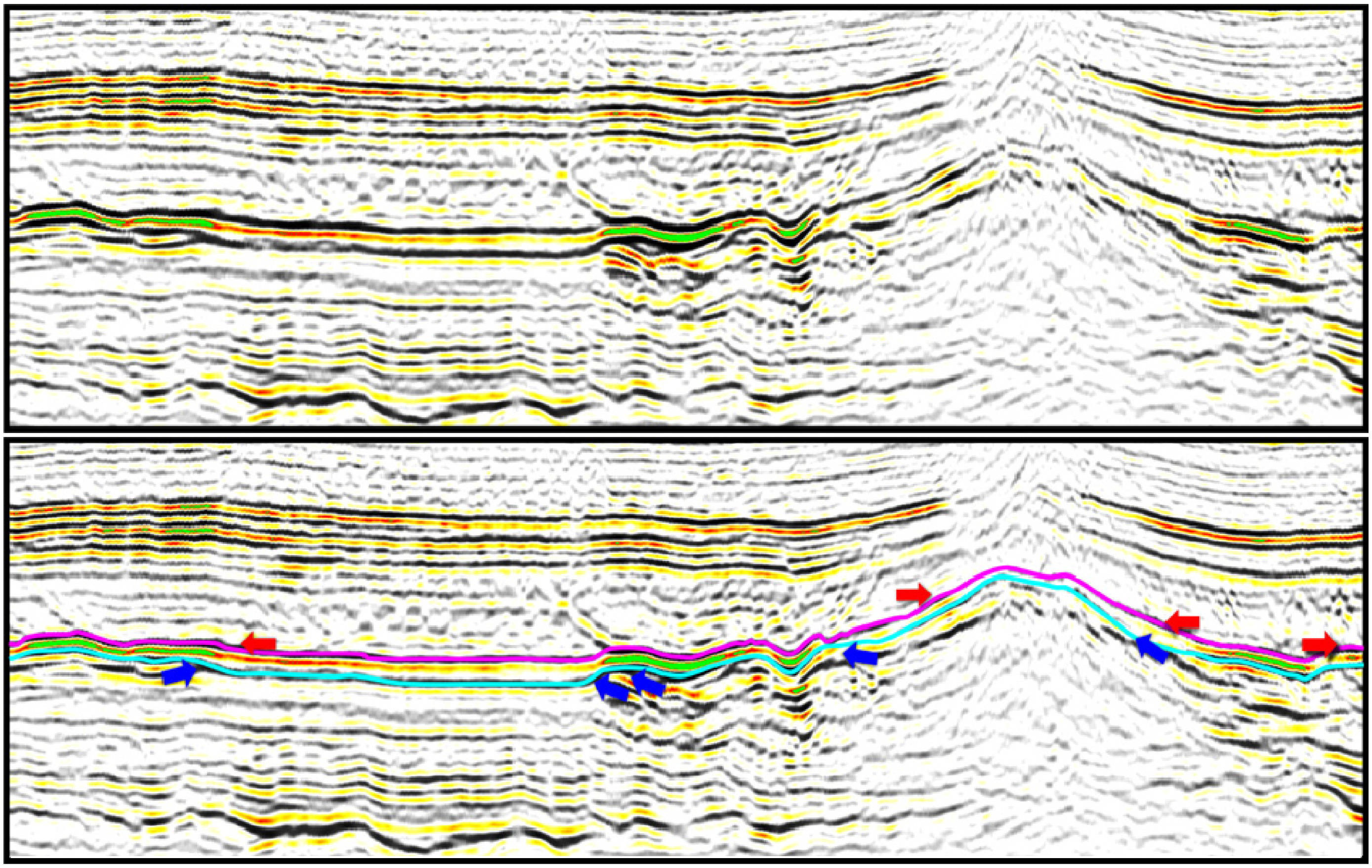


Figure 5. Uninterpreted and interpreted seismic line from the Green Canyon area showing distinguishing characteristics of a high amplitude reflector couplet that truncates seismic reflectors below (blue arrows) and is onlapped by reflectors above (red arrows). These reflectors are interpreted to represent the deposit resulting from the Chicxulub impact. Line is approximately 19 mi (30 km) across. Line location is shown in Figure 2.

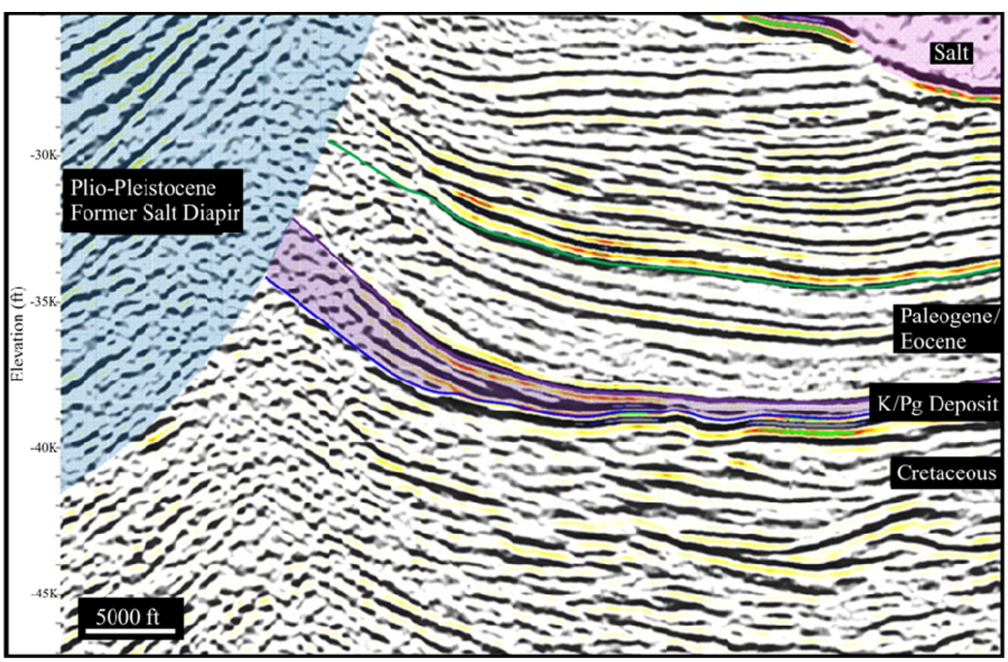


Figure 6. Seismic profile from the Keathley Canyon area showing an anomalous seismic facies at the top of the Cretaceous section interpreted to represent the deposit resulting from the Chicxulub impact. Line location shown in Figure 9. 5000 ft = 1524 m.

Alaminos Canyon 557 #1BP2 wells, particularly in the resistivity curves (Fig. 3). It must be noted that no wells in this study penetrated the interpreted seismic wedges and so may only represent the upper portion of the K/Pg boundary deposit.

If the seismic facies observed in the data represent the deposit of a geologically instantaneous event that filled in many if not most of the lows in the seafloor, it essentially is a cast of the seafloor topography at the time of the impact. The thickness and

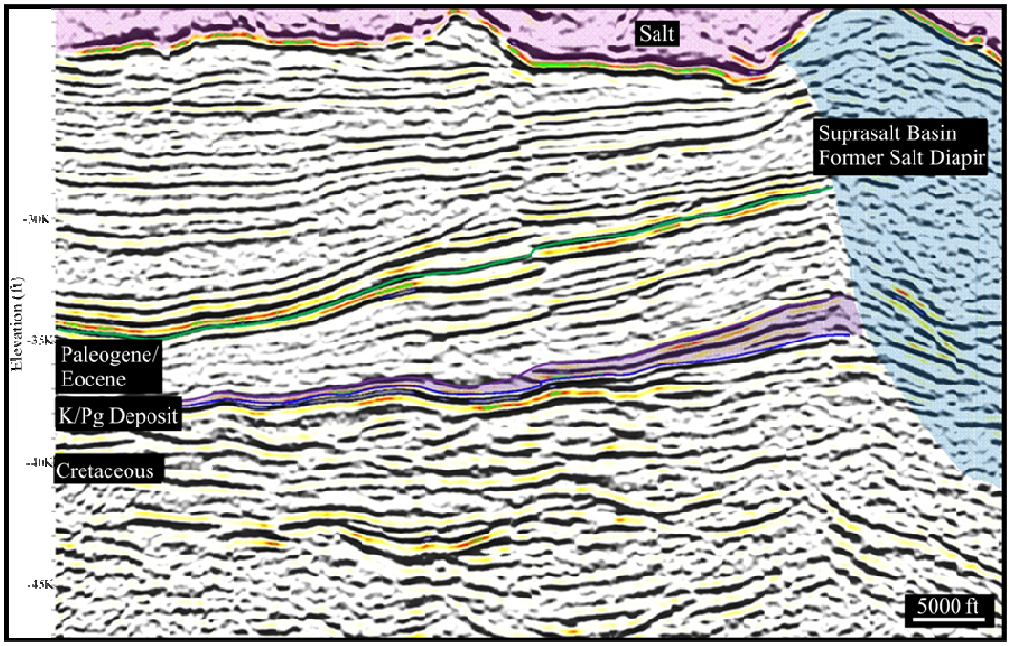


Figure 7. Seismic profile from the Keathley Canyon area showing an anomalous seismic facies at the top of the Cretaceous section interpreted to represent the deposit resulting from the Chicxulub impact. Line location shown in Figure 9. 5000 ft = 1524 m.

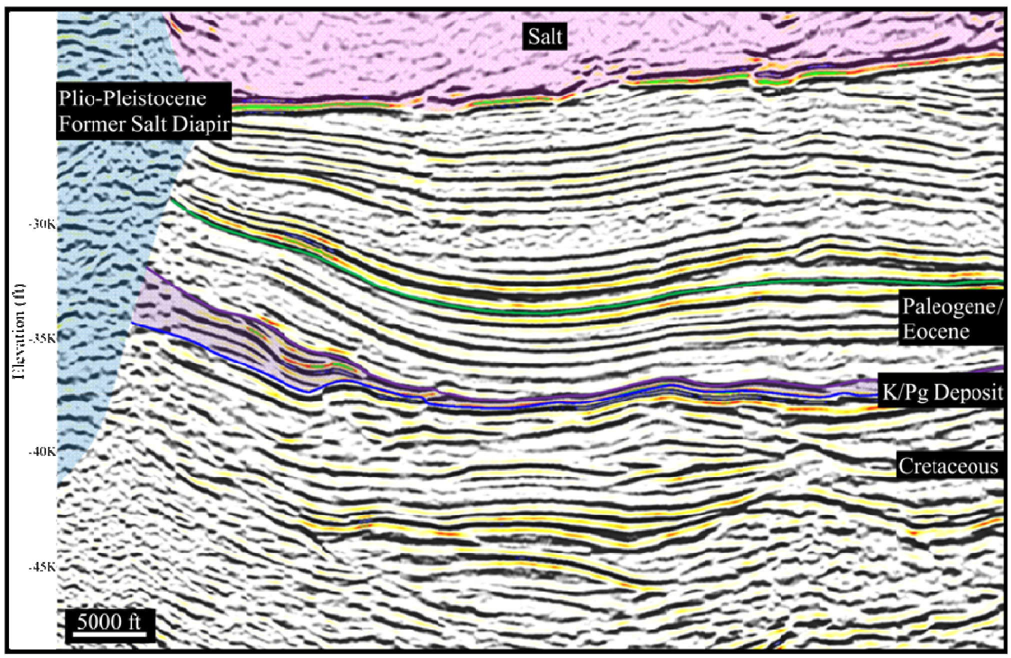


Figure 8. Seismic profile from the Keathley Canyon area showing an anomalous seismic facies at the top of the Cretaceous section interpreted to represent the deposit resulting from the Chicxulub impact. Line location shown in Figure 9. 5000 ft = 1524 m.

geometry of the seismic wedges indicate that numerous topographic lows existed in the seafloor in the north-central Gulf of Mexico in the late Cretaceous. At this geologic time, the seafloor in the north-central Gulf of Mexico most likely was dominated by topographic highs related to salt movement from the Jurassic-aged Louann salt (Hudec et al., 2013). Any sediment gravity flow (debris flow or turbidity current) initiated from the Chicxulub impact should have been influenced by the seafloor topography of the Gulf of Mexico that directed the path and influenced deposition of the flows. All of the currently observed seismic wedges are flanking diapirs of Jurassic-aged Louann salt which were active at the time of impact, as indicated today by deep sediment filled basins that sank into these diapirs in the Plio-Pleistocene, (Figs. 6–8). Upward movement of salt in the diapirs to keep pace with the accumulating sediment load around them (Hudec and Jackson, 2007) potentially created adjacent salt withdrawal basins in some fashion as the underlying salt moved from the original deposit location into the salt diapir and the space was subsequently filled with the sediment redistributed by the Chicxulub impact.

CHICXULUB IMPACT DEPOSITIONAL MODEL FOR THE NORTH-CENTRAL DEEPWATER GULF OF MEXICO

Pre-Impact

The sediment deposition through the Cretaceous across the north-central Gulf of Mexico is predominately carbonate muds with minimally varying thickness due to slow sedimentation rates (Goldhammer and Johnson, 2001) (Fig. 10a). Bathymetric variations in the seafloor are present with lows adjacent to seafloor

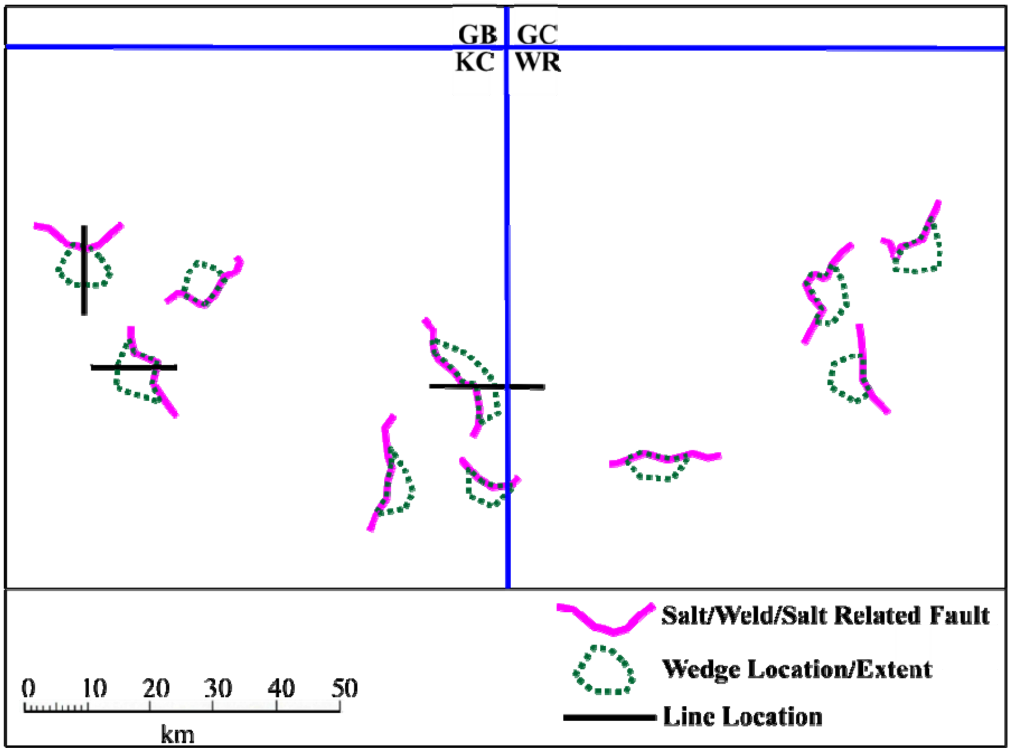


Figure 9. Outlines of the extent of the mapped anomalous seismic wedges interpreted to be the K/Pg boundary deposit and the relationships with adjacent salt features in the Keathley Canyon and Walker Ridge areas. Location of seismic lines in Figures 6–8 are shown.

highs related to the development of large (1–6 mi [2–10 km] wide based on interpretation of Plio-Pleistocene salt-withdrawal minibasins on seismic data) salt diapirs, the result of salt movement associated from the underlying Jurassic Louann salt deposit. The Late Cretaceous sediments of Maastrichtian to mid-Campanian age are primarily unconsolidated muds at this stage.

Impact (Minutes)

As a result of the collapse of the ~6 mi (10 km) wide by 19 mi (30 km) deep hole (Schulte et al., 2010) created by the impact, earthquakes waves radiated out from the impact center across the Gulf of Mexico and into North America shaking unconsolidated, water-laden sediments on the shelf and slope across the entire northern Gulf of Mexico. The ground movement across the Gulf of Mexico may have been severe enough to re-suspend some non-indurated sediments (probably of Maastrichtian to mid-Campanian age) (Fig. 10b).

Collapse of the Campeche carbonate platform (forming breccia deposits as seen in the Canterell Oil Field on the northwest Yucatan Peninsula [Grajales-Nishimura et al., 2000]) and probably the Florida carbonate platform as well (Denne and Blanchard, 2013) induced multiple tsunamis that traveled across the Gulf of Mexico at different speeds (Tada et al., 2002). Ejecta from the impact are spread outward from the crater with some entering the northern Gulf of Mexico waters.

Post-Impact Time Frame 1 (Hours to Days after Impact)

Sediment failures on local highs in the deepwater environment and across the continental slope resulting from the impact-induced earthquakes and multiple tsunamis produced sediment gravity flows (debris flows) and transported sediments, along with the larger ejecta material (e.g., glass spherules) that had fallen through the water column to the ocean bottom, to the available accommodation space created by the movement of salt in the deepwater Gulf of Mexico (Fig. 10c). The different sediment supply areas, local highs, and slope and shelf areas, had transport paths of different lengths that resulted in layering of varying compositions as the sediment gravity flows from the different sediment source areas arrived in receiving basins at different times. The coarser-grained clasts (medium? to fine grains) are deposited while the very fine-, silt-, and clay-sized component of the induced sediment gravity flows are preferentially lifted higher into the water column.

Post-Impact Time Frame 2 (Days to Weeks after Impact)

Ejecta material and re-suspended sediments (very fine to silt sized) settled onto the sea floor through the water column draping most locations (Fig. 10d). Sediment gravity flows caused from the initial and continued seismic instability and possible tsunami perturbations continued to transport sediments from the shelf and slope sources to the available accommodation space in the deepwater Gulf of Mexico. Backwash from tsunamis potentially brings onshore material into the deepwater Gulf of Mexico (c.d. Schulte et al., 2010).

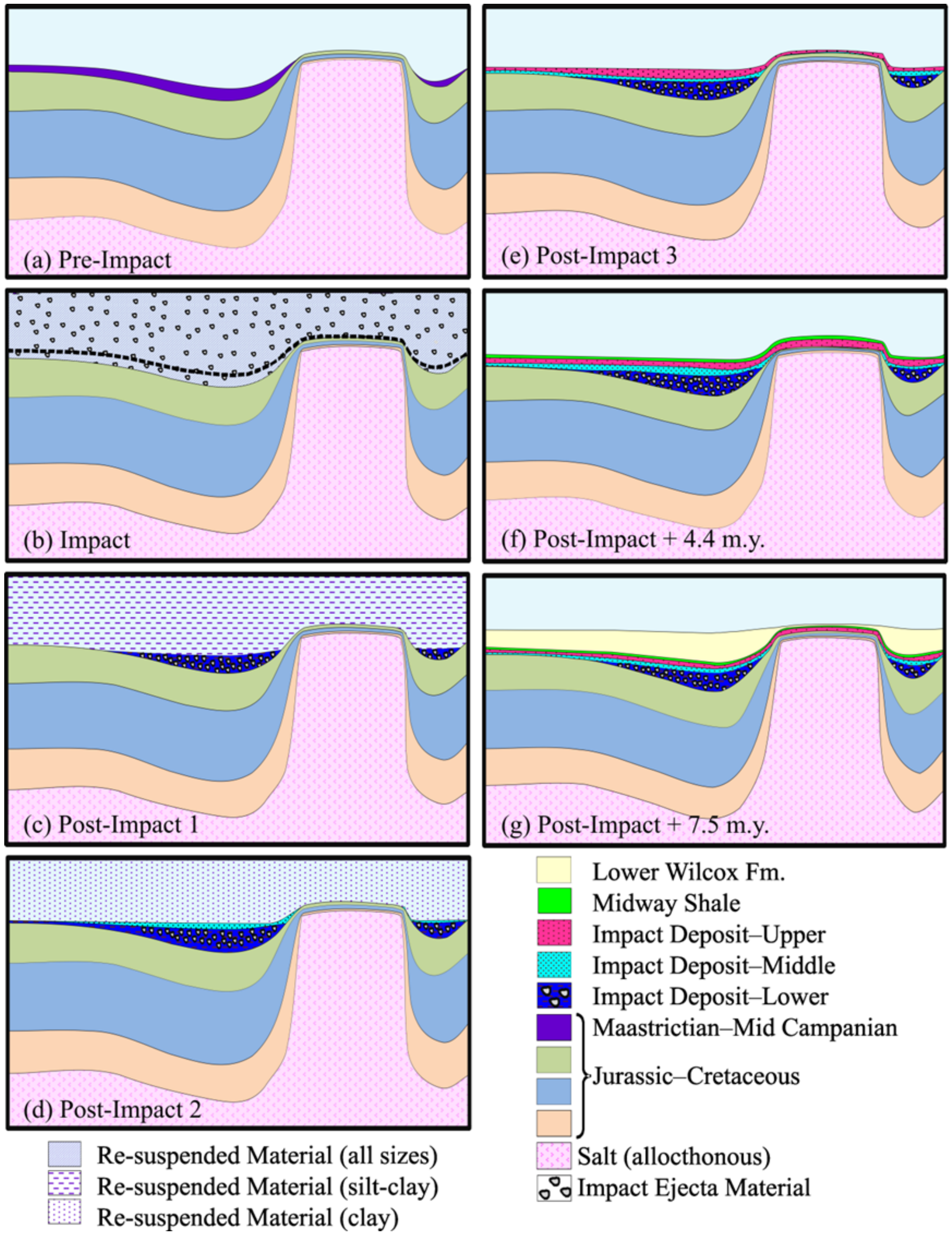
Post-Impact Time Frame 3 (Weeks to Months after Impact)

Seismic instability and residual tsunami effects recede and sediment gravity flows diminish as all sediment that could have moved has probably done so. The finest-grained sediments (clay sized) settle from the water column onto the sea floor draping most locations (Fig. 10e).

Post-Impact Time Frame 4 (Next 4.4 m.y.)

Over the next 4.4 million years, only minor accommodation space is created even with the differential load of the impact deposit on the Louann salt due to the rigidity of the underlying Cretaceous sediments distributing the load. With all the non-indurated sediments previously mobilized, very limited sediment gravity flows occur. A thin condensed layer, informally designated as the Midway Shale, is deposited across the north-central Gulf of Mexico (Fig. 10f).

Figure 10. Depositional model for the Chicxulub impact deposit in the deepwater Gulf of Mexico for (a) pre-impact, (b–e) immediately post-impact from minutes to months, and (f–g) post-impact from months to ~7.5 m.y. See text for more detail.



Post-Impact Time Frame 5 (4.4 m.y. to 7.5 m.y. after Impact)

Large volumes of sediment are brought into the north-central Gulf of Mexico and are transported and distributed far into the Gulf of Mexico deep basin. Siliciclastic deposits of the Lower Wilcox Group fill in the remaining bathymetry created after the impact event, bury some of the bathymetric highs and add to the differential load onto the underlying Louann salt driving the subsequent salt movement and future accommodation space creation (Fig. 10g).

EFFECT OF THE IMPACT DEPOSIT ON THE GULF OF MEXICO SEA FLOOR

The north-central Gulf of Mexico was undergoing allochthonous salt movement that was expressed in numerous salt highs and variable topographic features on the sea floor (Hudec et al., 2013), when the Chicxulub bolide impact occurred. The basin-wide redistribution of sediments through sediment gravity flows and suspension fall out moved all the unconsolidated deposits and eroded material from local, shelf, slope and potentially onshore sources into the deep basin, transporting them across the topographically rugose sea floor. The sediment redistribution initiated by the Chicxulub impact blanketed the entire northern Gulf of Mexico filling in all available accommodation space on the slope (salt-related minibasins) smoothing out the sea floor between the prominent salt highs but not completely cover all the existing topography. The overlying clastic sediments of the Paleogene/Eocene Wilcox Group were funneled along the uniform seafloor through sediment fairways defined by the remaining salt highs from the shelf, across the slope and into the deepwater (Fillon and Lawless, 1999).

The more uniform bathymetry resulting from the filling of available accommodation space on the shelf and slope established an efficient transportation pathway for the Wilcox Group sediment gravity flows. The turbulent energy of the sediment gravity flows moving down this transportation path could be maintained on the slope as the flow was weakly confined by the remaining unburied salt highs. As the sediment gravity flows moved past the seafloor influenced by the salt highs and exited these corridors they lost topographic confinement and formed large (>60 mi [>100 km] wide) submarine fan complexes that coalesced across the continental rise (Zarra, 2007) (Fig. 11).

FUTURE WORK NEEDED

A better understanding of a number of potential influences on the sedimentary processes triggered by the Chicxulub impact can further refine the proposed depositional model. While the triggering mechanism for the sediment gravity flows that deposited the impact deposit is well established, understanding the exact effect of the impact induced earthquake as well as the scale and amount of any aftershocks across the Gulf of Mexico and North America to deduce ground movement is needed. The multiple carbonate platform and shelf edge collapses (e.g., Campeche Escarpment, the Florida Escarpment, and the Texas-Louisiana shelf) would have created separate tsunamis that traveled across the Gulf of Mexico. The interaction of these tsunamis (and any subsequent reflected waves) may have constructive or destructive interference and influenced the size of induced sediment gravity flows in certain areas. Bathymetry of the Gulf of Mexico and configuration of the shoreline would influence the volume of available sediment for relocation into the deepwater environment. Of particular interest to understand the impact of the tsunamis on sediment supply is identifying the extent of the Cretaceous Seaway at the time of impact and the distance a tsunami might travel landward and then transport sediment in the backwash into the Gulf of Mexico. For petroleum systems analysis, definition and understanding of the mechanics of the salt structures present at impact and their seafloor expression is needed in local areas of the north-central Gulf of Mexico to understand the interaction of sediment gravity flows with bathymetry for better prediction of sediment fairways and depositional patterns immediately after the impact as well as during the deposition of the Wilcox Group.

SUMMARY

The sedimentological events initiated by the Chicxulub impact were all produced from geologic processes that are well understood and that have occurred through the history of the earth. The extraordinary aspects of this event are the scale that was involved and the very short time duration. The Chicxulub impact initiated nearly simultaneous movement of sediment over an immense geographic area in a geologically instantaneous time frame, resulting in the most extensive single depositional event in the history of the Gulf of Mexico and potentially the largest single event recorded in the rock record (Denne et al., 2013). After the impact deposit, only pelagic and hemi-pelagic sedimentation occurred for the next 4.4 m.y. across the north-central Gulf of Mexico (the Midway Shale). The authors speculate that the Chicxulub impact triggered all the potential sediment gravity flows across the entire northern Gulf of Mexico that would have occurred under normal conditions over approximately the next 4.4 m.y. to happen in a time span of weeks to months due to the most significant single geologic event that the Gulf of Mexico has experienced to date.

ACKNOWLEDGMENTS

The authors would like to thank Marathon Oil Corporation for permission to publish this study, Kirt Campion and John Breyer for their helpful conversations, and John Snedden, Thom Yancey, and Gary Kinsland for their reviews of the paper. The authors are grateful to April Smith who worked many hours on the figures.

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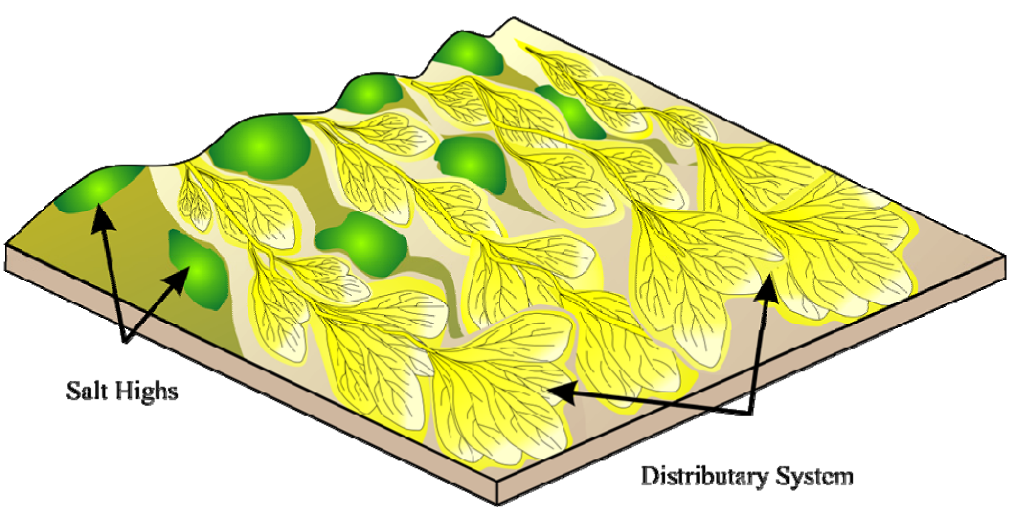

Figure 11. A model for movement of clastic sediments of the Paleogene/Eocene Wilcox Group transported along pathways from shelf to deepwater environments as a result of the impact deposit filling in and smoothing out the seafloor topography. As the sediment gravity flows exited the fairways defined by salt highs they formed coalescing distributary complexes.

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