RICE UNIVERSITY

SEISMIC STRATIGRAPHY OF THE
NORTHWEST GULF OF MEXICO

by

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A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE

MASTER OF ARTS

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April, 1985

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ABSTRACT

Pleistocene sedimentation at the outer continental shelf of the northwest Gulf of Mexico was related to eustatic fluctuations of sea level during the Wisconsin period. Four seismic sequences interpreted from high resolution records corresponded to deposition during a Recent high sea level stand, a late Wisconsin low sea level stand, a middle Wisconsin interglacial high stand, and the forth sequence was evidenced by the record of deposition during an early Wisconsin low sea level stand.

Growth faulting, seen as expansion of section, and a more prevalent faulting due to salt diapirism were present throughout the study area. The growth faults were consistent through the sections. Faults related to diapirism were local and many were not traceable from section to section. Both growth faulting and diapirism, as well as eustatic sea level changes, seem to have exerted an influence on sedimentation in the study area.
The fine members of my thesis committee merit first mention. Professors Anderson, Clark and especially committee director Professor Bally have demonstrated exceptional patience and willingness to help a non-traditional student. The members of my committee have always been available to share their time to answer questions and offer assistance.

Special thanks is due Texaco, Inc. and J.R. Rogers for allowing use of the high resolution seismic records. The study could not have started without their donation.

Thesis support from the Gulf Coast Association of Geologic Societies was used to fund reproduction expenses. I thank GCAGS's Edward C. Roy and Clyde E. Harrison for their support and confidence.

Correlation of this study area and that of Lewis was made possible by the efforts of Henry L. Berryhill of the Mineral Management Service, Corpus Christi. I am grateful for his assistance. Dr. Berryhill presented his data and gave guidance which allowed confidence in interpretation.


This study is similar to that of Dana Lewis, Rice' 84. I must thank her for the time spent in
discussion and for her guidance. Hopefully, I may have helped her as much as she aided me.

Credit must be given John A. Conner. John allowed me to see the value of finishing the work towards a degree. John demonstrated confidence in me when it was most needed.

Final mention is for my wife. Sally has been in the background giving support throughout my studies. I can hardly thank her enough.
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INTRODUCTION

The purpose of this study was to describe the relation of sedimentation to faulting, diapirism, and eustatic sea level changes exhibited by the upper Pleistocene sediments of the outer continental shelf of the northwest Gulf of Mexico. Using the technique of Mitchum, Vail, and Sangree (1977), high resolution seismic records have been interpreted to define seismic sequences; these sequences were used as the basis for stratigraphic evaluation. The grid of seismic lines furnished by Texaco, Inc., presented sediment sequences which could be correlated from one end of the study area to the other. The deposition of the sediments has been affected by climatic changes that have been postulated for the late Pleistocene period. Using climatic history and the internal and external geometry of the sequences, an interpretation which suggests deposition in a regime of eustatic sea level change is indicated. The collateral effects of diapirism and faulting, both growth faulting and faulting associated with diapirs, are shown to have also influenced sedimentation.
PREVIOUS WORK

Paleoclimatology

The Pleistocene paleoclimatic history of the Gulf of Mexico was dominated by the periodic oscillation between glacial and interglacial ages (Thunell, 1984). Evidence for climatic change includes micropaleontologic studies on specific and morphologic variability, oxygen isotope studies, and correlation of continental and marine glaciation.

Micropaleontologic evidence for climatic change was presented by Thunell (1984) and Malamgren and Kennett (1976). These authors derived principle component planktonic foraminiferal assemblages that were clearly temperature related (Figure 1). Beard (1969) and Kennett and Hudleston (1972) demonstrated resolution of cold and warm water cycles based on the presence of climatically sensitive planktonic foraminiferal species. Beard and others (1982) produced paleotemperature records for the entire Pleistocene that have been correlated with the North American glacial stages (Figure 2).

Williams (1984) estimated 70-90% of the signal recorded in isotopic composition was due to sea
Figure 1. Comparison of late Pleistocene paleoclimatic curves. In all cases, warm is to the right and cold is to the left (from Thunell, 1984).
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After Thunell, 1984
Figure 2. Comparison of mid-continental and Gulf of Mexico glacial-interglacial stratigraphy (from Beard et al., 1982).
after Beard, 1982
water composition changes as a result of the change in continental glaciation. Warm periods were indicated by lower isotopic values. The rapid influx of melt water from the Laurentide ice sheet resulted in a decrease in the ratio between the light and heavy isotopes of oxygen in the Gulf waters (Figure 3). Cooler periods are noted by the relatively higher isotopic values as the lighter oxygen is precipitated in expanded glaciated areas.

Sea Level Change

The Pleistocene glacial periods locked great quantities of water as both land and oceanic ice. Flint (1971) estimated the Laurentide ice sheet volume at 27 million cubic kilometers. The ice cover of grounded glaciers could have accounted for major worldwide lowering of sea level. The modern shelf break for the Gulf of Mexico is assumed to be located at the 180 meter (600 foot) bathymetric contour line; this would indicate a maximum possible sea level rise if the shelf edge was exposed during the most recent glacial stage. Pitman (1978) indicated at least a 50 meter fall in sea level could be postulated for glacial effects. Sea level changes by other mechanisms were accounted for by Pitman as having been caused by
Figure 3. Oxygen isotope record from the Gulf of Mexico for approximately the last 25,000 years. Shaded area reflects the input of isotopically depleted glacial melt water (from Williams, 1984).
after Williams, 1984
volume changes in mid-oceanic ridges, rates of sedimentation, and active and passive margin subsidence. The rates of sea level change by other means were slow (1,000,000 yrs.) in comparison to those during the glacial stages (1000 yrs.). Pitman indicated a rate of sea level fall due to deglaciation in the order of 10m./1000 yrs. Volume change in ice is accepted as the cause of Pleistocene sea level variability.

Beard and others (1982) equated periods of continental glaciation with a relative fall in sea level; deglaciation was equated with a rise in sea level. If one accepts Beard, et. al. dating for the Pleistocene, eight couplets of rise and fall in Gulf Coast sea level can be noted in the Pleistocene sedimentary record. Harmon and others (1977) have carbon dated three major periods of high sea level during the last 200,000 years; between these high stands were two periods of low sea level. Both Beard and Harmon postulated long periods of low stand in comparison to the shorter duration of high sea level. Both related a rapid fall in sea level with glaciation and a slow rise in sea level with deglaciation.
Eustacy and Sedimentation

Seaward movement of the shore is associated with a fall in sea level (assuming subsidence equals sedimentation rate). Concurrent with the lowering sea level, sedimentary patterns could be expected to change. Rivers will entrench over the exposed continental shelf and a new deposition area for the sediment load established. If the drop in sea level is rapid, the shoreline may be expected to be near the shelf break (Pitman, 1978), and in the extreme case, fluvial sediments may be deposited on the continental slope. The increase in gradient will permit deposition of coarser sediments directly on the slope. Sediment slides and turbidity currents would be more likely agent during low stands (Reineck and Singh, 1980), hence a more chaotic sediment layer will be deposited. The old coastal plain may become an area of erosion rather than deposition (Suter and Berryhill, 1985). Wave action will be concentrated at the shoreface and wave base would have a reduced effect on the much deeper sea bottom. (Reading, 1978). Because of the decreased effect of wave action, upper slope sediments will be less widely dispersed from their source. Flood plain overbank deposition at the outer continental shelf could cause an upbuilding
of sediment. The deltaic deposition will cause an outbuilding of the delta front. Shoreward movement of the strandline is associated with a rise in sea level. Under these conditions, river valleys will be flooded to become estuaries, and course sediments will again be largely deposited in delta mouth bars situated on the inner continental shelf. These point sources of sediment will fill in local areas of the shelf. Most of the shelf will be sediment starved (Hay and Southam, 1975). A thin, transgressive, more wide sediment sequence will be deposited through the action of the waves, long shore currents, and pelagic sedimentation (Reineck and Singh, 1980). The new transgressive and older regressive sediment starved continental shelves are covered with these "relic" sediments. Emery (1968) indicated 70% of the transgressive sediment starved continental shelves are covered by these "relic" sediments. Emery illustrated (Figure 4) that the continental shelf of offshore Louisiana is covered by Holocene fine grained sediments. As the sediment supply continues to fill the local area, the deltaic sequences will prograde up and out to cover these transgressive sediments (Beard, 1982). Similar to low sea level sedimentation, deposition
Figure 4. Sediments of the continental shelf Gulf of Mexico. Diagonal hatching indicates areas of relic sediments; dots show areas of modern sands; dashed horizontal lines depict areas of modern silts (from Emery, 1968).
GULF OF MEXICO

after Emery, 1968
of the clastic material will be thicker nearer the sediment source.

Progradation of deltaic sediments requires a sedimentation rate in excess of subsidence. Progradation can occur during sea level rise if the rate of rise of sea level and/or subsidence is less than the rate of deposition (Pitman, 1978). The excess sediment can be deposited in two areas, at the delta outlet or overband. Large sediment rich deltas, such as the Mississippi Delta, build lobes that prograde seaward. Lindsay and others (1984) estimated 37 cm./yr. average accumulation rate at the the distributary-mouth bar and progradation of a 1.8 km. (1 mi.) in 75 years. The prodeltas are sites of very rapid deposition of low density, underconsolidated, clays and silts. As the delta continues to prograde, coarser, higher density sediments are deposited upon the low density fines. The large quantities of fine sediments can become overpressured if adequate compaction time is not available. Failure as slides is common.

Growth Faulting

Listric growth faults are a common structural
element in the northwest Gulf of Mexico. They are characterized by an increase in sediment thickness on their downthrown side. The difference in sediment thickness is result of movement on the fault contemporaneous with sedimentation. The downthrown side may typically show rollover or reverse drag and rotation. Growth faults demonstrate expansion of section in kilometers (thousands of feet) (Edwards, 1981) and exhibit surface traces in tens to hundreds of kilometers (Kraft, 1979). The trace is parallel or sub-parallel to the coast. The throw of the fault is usually normal and down to the basin. Bally (1981) indicated growth faults interact with diapiric structures, most are predominately associated with gravity tectonics.

Bruce (1973) postulated differential loading and compaction may trigger growth or contemporaneous faulting. The undercompacted fine sediment becomes overpressured and undercompacted by a progression of denser overlying materials. The fine material will downwarp, flow, and finally fault. The fine material acts as a detachment surface and the fault is listric, having a high angle at its upper surface expression and curves concave toward the coast to a low angle at the
detachment surface (Figure 5).

The formation of growth faults may also be explained by a gravity sliding mechanism. The internal angle of friction in the overpressured fine material can be reduced due to the inability to dewater. Grains will be held apart by the fluid rather than exhibiting the stronger grain to grain contact. With increased overburden, shear strength will decrease as the pore pressure increases. The fine material will experience failure and move downslope.

Lehner (1969) related growth faulting to salt ridges present in slope areas. Although the individual diapirs did not cause growth faulting, lateral salt flow away from areas of sediment loading may have been influential. Winkler and Edwards (1982) related growth faulting, salt withdrawal, sediment compaction, and subsidence. Growth faulting may have more than a singular mechanism to explain the formation of a specific fault or fault system.

Diapirism

The structural style of the northwest Gulf of Mexico is notable due to the presence of salt structures. Seni and Jackson (1983) proposed three
Figure 5. Diagrammatic cross section depicting growth faulting, Gulf of Mexico basin (from Bruce, 1984).
after Bruce, 1984
structural genetic stages for salt structures for East Texas (Figure 6). Following Sannemann (1968) and Trusheim (1960), Seni and Jackson described a pillow as the earliest formative stage. The pillow exhibits stratal onlap and crestal erosion or thinning which may be indicative of syndepositional sedimentation. An area surrounding the swell forms the primary peripheral sink. The diapir develops by salt withdrawal from the pillow flanks. The withdrawal area forms a large secondary peripheral sink. The diapir may intrude sediments of low competence. Sediment units near the crest thin either due to syndepositional or postdepositional factors. Post diapir stages are noted by a tertiary withdrawal sink and steady state movement. The domal crest remains the same depth regardless of subsidence or salt availability.

Woodbury (1973) illustrated three coast-parallel provinces differentiated on salt structures (Figure 7). Closest to the coast line is a band of isolated stocks. The second province is composed of isolated stocks associated with growth faults. The third province, located at the shelf edge and slope, is an area of large semi-continuous uplifts. Lehner (1969) described broad swells and pillows for the diapirs located at the slope.
Figure 6. Schematic stages of dome growth (from Seni and Jackson, 1983)
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<th>WITHDRAWAL BASIN</th>
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<td>Geometry</td>
<td>Sediments above pillow are thin over broad, equidimensional to elongate area. Maximum thinning over crest. Area extends 100 to 400 km² (40 to 150 mi²), depending on size of pillow. Percentage thinning, 10 to 100%.</td>
<td>Sediments are overthickened in broad to elongate primary peripheral sink, generally located on updip side of salt pillow. Axial trace of sink parallels axial trace of elongate uplift, generally separated by 10 to 20 km (6 to 12 mi). Sink attains 300 km² (120 mi²) in extent, depending on size of pillow. Percentage thickening, 10 to 30%. Recognition of primary peripheral sink may be hindered by interference of nearby salt structures.</td>
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<td>Facies</td>
<td>Thin, sand-poor, fluvial-deltaic deposits over crest of pillow include interchannel and interdeltaic facies. Erosion common. Carbonate deposits on crest would include reef, reef-associated, and high-energy facies.</td>
<td>Thick, sand-rich, fluvial-deltaic deposits in primary peripheral sink include channel axes and deltaic depocenters. Aggradation common in topographically low area of sink. Carbonate deposits in sink would include low-energy facies caused by increase in water depth.</td>
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| **DIAPIR**   |              |                 |
| Geometry     | Strata largely absent above dome. An 8 to 50 km² (3 to 20 mi²) area around diapir is thinned, depending on size and dip on flanks of dome. | Sediments are thickened up to 215% in secondary peripheral sink. Sinks up to 1,000 km² (390 mi²) in extent are equidimensional to elongate, and they preferentially surround single or multiple domes; several sinks flank domes; percentage thickening ranges from 30 to 215%. |
| Facies       | Facies immediately over dome crest not preserved because of piercing by diapir of all but the youngest strata. Sand bodies commonly pinch out against dome flanks. | Expanded section of marine facies dominates, including limestones, chalks, and mudstones; generally sink is filled with deeper water low-energy facies caused by increased water depth. Elevated saddles between withdrawal basins are favored sites of reef growth and accumulated high-energy carbonate deposits. |

| **POST-DIAPIR** |              |                 |
| Geometry     | Strata thin or absent in small 10 to 50 km² (4 to 20 mi²) area over crest and adjacent to dome; area depends on size of dome and dip of flanks. | Sediments within 20 to 200 km² (8 to 80 mi²) tertiary peripheral sink are thickened 0 to 40%, commonly by < 30 m (100 ft). Axial trace of elongate to equidimensional sink surrounds or flanks a single dome, or connects a series of domes. |
| Facies       | Facies and strata over crest of dome not preserved in places of complete pierce- ment. Modern analogs have interchannel and interdeltaic facies preserved in places of 50° ± 30° diapir. Modern analogs have interchannel and interdeltaic facies in uplifted area. Mounds above dome include thin sands. Carbonate strata would include reef or high-energy deposits; erosion common. | Modern analogs have channel axes in sink. Aggradation of thick sands common in subsiding sink. Carbonate strata would include low-energy facies. |

Seni and Jackson, 1983
Figure 7. Distribution of salt diapirs northwest Gulf of Mexico (from Woodbury, et al., 1973).
after Woodbury, 1973
Amery (1976) divided slope salt structures into an upper slope province with large interconnected salt swells and a lower slope province with more closely spaced shallow swells. The structures vary depending upon sediment loading. Upper slope salt has been covered by prograding shelf sediments while lower slope salt did not receive nearly as much overburden. Antoine (1974) illustrated closely spaced salt pillow at the lower slope and wider spaced diapirs at the shelf break (Figure 8). Humphris (1975) showed sediment overburden as it effects salt flowage and salt structure (Figure 9). Humphris related the formation of diapirs with sediment downbuilding.

Suter and Berryhill (1985) related salt diapirism as the controlling factor for fluvial and deltaic sedimentation in the northern Gulf of Mexico. Lehner (1969) indicated the broad swells of the slope influenced downslope sedimentation from slides and turbidity currents. The topographic highs and low formed due to salt extrusion and withdrawl propogate conduits for sediment movement. Mounds formed due to salt uplift may have several effects, according to Seni and Jackson (1983). Subareal mounds will divert streams. The mounds will be sand starved and the
Figure 8. Irregular surface topography caused by differential salt movement (from Antoine et al., 1974).
after Antoine et al., 1974
Figure 9. Salt dome growth as a result of sediment loading on upper slope and shelf (from Humphris, 1975).
SEDIMENT LOADING

SHELF SLOPE

INITIATION OF DOMES

SALT FLOWAGE

BASE SALT

after Humphris, 1975
fluvial channels in depressed areas sand rich. The opposite may have happened under marine conditions. Winnowing of sands may occur on the topographically high swells.

Halbouty (1976) described process of salt tectonism and characterized piercement shapes of fault patterns (Figures 10 and 11). He provided major synthesis of specific Gulf Coast province salt domes.
Figure 10. Idealized section showing structural and stratigraphic variability associated with salt domes (from Halbouty, 1967).
Idealized section showing common types of hydrocarbon traps associated with salt domes. Various traps include (1) simple domal anticline draped over salt, (2) graben fault trap over dome, (3) porous cap rock, (4) flank sand pinchout and sand lens, (5) trap beneath overhang, (6) trap uplifted and buttressed against salt plug, (7) unconformity, (8) fault trap downthrown away from dome, (9) fault trap downthrown toward dome.

after Halbouty, 1967
Figure 11. Map of central graben and complex radial fault pattern over salt dome (from Halbouty, 1967).
CONTOUR INTERVAL 200 FEET

after Halbouty, 1967
The offshore Louisiana continental shelf has been described as a series of prograding sediments deposited during glacial eustatic events. Diapirs and faults may have influenced the depositional processes. Seismic records allowed interpretation of the effects of structure and sedimentation processes. The following section outlines the technique used for interpretation. The technique is presented in more detail in the Appendix.

Mitchum, Vail, and Thompson (1977) defined their concept of seismic sequence. Genetically related strata are bounded by conformities and unconformities at the upper and/or lower boundaries of the sequence. An unconformity at the sequence boundary is noted by stratal termination or lapout.

In this study the strata were analyzed to determine reflection terminations and unconformity surfaces. The unconformity surfaces allowed discrimination of the strata into separate sequences. Four sequences were thus defined.

Seismic sequences are characterized by an internal form and reflection configuration. The pattern of internal configuration is characterized in seismic facies analysis. Each sequence was
analyzed to determine the internal reflection configuration and the seismic facies were mapped. Clinoform patterns, parallel reflection configurations, and toplap were the prevalent internal form assumed within the sequences described in this study.

The clinoform configurations were interpreted to suggest deltaic sedimentation on a continental shelf or prograding slope. Parallel reflections were interpreted to suggest hemipelagic sedimentation. Toplap was present in areas of clinoform configuration and in regions interpreted as subsiding continental shelf. Maps were constructed to outline the area of occurrence of the various facies for each sequence.
Using the technique presented in the previous chapter and the Appendix, 3200 line kilometers (2000 miles) of high resolution seismic section were analysed to determine seismic sequence boundaries and seismic facies. Each seismic line was interpreted separately and the boundaries of seismic sequences correlated through the grid of lines. Seismic facies were analysed and mapped. Isopach maps of each sequence were constructed. The travel time through each sequence sediment was measured vertically and converted to depth using a 1700 m./s. (5580 ft./s.) velocity of sound in sediments (Bouma, et al., 1983). A fault map was constructed. Faults which offset sediment surface were differentiated from faults without surface sediment influence. A map was constructed to illustrate areas of diapiric influence on sedimentation.

The geographic site for the study was the Gulf of Mexico offshore Louisiana (Figure 12). The seismic lines were oriented north-south (dip section) and east-west (strike section). The grid pattern (Figure 13) extended from the western half of South Timbalier South Addition through the south
Figure 12. Map of offshore Louisiana showing tract pattern.
Figure 13. Line drawing of grid pattern.
additions of Ship Shoal and Eugene Island to the western boundary of South Marsh Island South Addition (Figure 14). The grid pattern encompassed approximately 8500 square kilometers (3000 square miles) of coverage. Line spacing was 2.8 kilometers (1.8 miles) north-south, while the east-west tie lines were spaced on average 12 kilometers (7.5 miles).

The seismic data consisted of analog, paper recorded, 500 and 750 millisecond records. A ten or forty cubic inch airgun was used for the power source. Frequency was limited to 70 to 500 Hz. by a band pass filter.

Several features were noted on each seismic line (Figure 15). The first reflection was the direct arrival of the seismic signal from the airgun through the water column to the hydrophone. The seafloor or water bottom was seen as the next signal. The signal from the water bottom was characterized by three cycles of reflection amplitude.

The sequences generally repeated the three cycles of reflection amplitude at their boundaries. Below the primary reflections of the sequences, the first water bottom multiple was seen. The sequences and water bottom multiples were repeated through
Figure 14. Map of south additions of offshore tracts with block numbers. Line 740X extends north from South Marsh Island block 199; line 304X extends north from South Timbalier Block 307.
Figure 15. Multiple reflections of seismic sequences. Primary sequence boundary reflections labeled with numerically; multiple sequence boundary reflections labeled alpha-numerically.
the seismic section. The repetition of primary reflections as multiples resulted in masking of data below the first seafloor multiple. The interpretation of seismic data was generally limited to reflection above the first water bottom multiple.

Ringing at interfaces also masked data. The three cycles of ringing (Figure 16) at the sediment-water interface obscured approximately 15 meters (50 feet) of sediment. Ringing at sequence boundaries masked 12 meters (40 feet). The ringing was caused by the air bubble collapse and expansion after release by the airgun.

Having used three cycles of wave amplitude for 15 meters of travel, a wavelength of 5 meters (17 feet) was approximated for the sonic impulse. With a resolution to one half wavelength, strata 2.4 meters (8 feet) was determined as the limit of resolution.

The seismic sections demonstrated vertical exaggeration. The vertical extent of diapir uplift is presented as an example. Figure 17 demonstrates the exaggeration at various scales. Figure 17 is a line drawing of the diapir illustrated in Figure 19.
Figure 16. Sonic ringing at water-sediment interface and seismic sequence boundary. Water-sediment interface ringing (uppermost triplet) obscures approximately 15 meters (50 feet) of data; ringing at sequence boundary covers 12 meters (40 feet) of data.
Figure 17. Line drawing depicting effect of vertical exaggeration at various scales.
Diapirs

A bathymetric map (Figure 18) shows a relatively smooth seafloor continuing in a southern direction. Near the 120 meter (400 foot) contour line the seafloor gradient increases from a 0.2 % slope to one of 0.5 %. The steepest gradient (1%) occurs in the south-central section of the study area. In this region a diapir was seen to subcrop to 91 meters (300 feet). The depression to the south has a depth of 240 meters (800 feet). This area is similar to the sediment conduits reported for the upper slope (Lehner, 1969). The depression is positioned between diapirs on either side.

The convoluted pattern of the 120 meter (400 foot) bathymetric line has been caused by diapiric influence on the seafloor topography. Another diapir was indicated by the style of the 91 meter (300 foot) isobath in the south-west corner of the study area. The 120 meter (600 foot) isobath generally demarked the southern extent of the study area. The seismic lines which extended beyond this isobath indicated rapid increase in water depth. The 120 meter contour line approximates the modern continental shelf edge.

Two provinces differentiated on the style of diapir configuration were discerned. Diapirs
Figure 18. Bathymetric map of study area. Contour interval 100 feet (30 meters). Constructed using 4900 ft/s (1500ms) sonic velocity in saltwater.
located near the shelf break tended to influence surface sediments (Figure 19). The diapirs projected up to form sea floor surface highs. The sediments tended to pinch out toward the diapir. The sediments were thicker in the tertiary withdrawal syncline as described by Seni and Jackson (1983).

Diapirs located landward from the shelf edge indicated little change in sea floor topography (Figure 20). The sediments tended to exhibit a constant thickness. The diapir uplifted the sediments to form an anticlinal structure. These diapirs usually were associated with more intense faulting in the area. Both provinces indicated a zone of influence on sediments near the diapir. Figure 21 illustrates sediment onlap toward the diapir. The sediment dips away from the diapir toward the synclinal area. Figure 20 shows sequence dip away from the diapir.

Figure 21 shows the location of channels in the northern half of the study area. The channels trended around the periphery of the diapirs. On seismic section the depth of the channel was difficult to interpret. Figure 22 illustrates a channel with an depth of approximately 30 meters (100 feet). The channel demonstrated maximum
Figure 19. Shelf edge diapir with sequence sediment thinning and pinchout toward crest of diapir.
Figure 20. Seismic section of diapir located on continental shelf.
Figure 21. Map of diapir location, continental shelf/upper slope. Note southern province of continuous diapirs and landward province of isolated diapirs and channels. Sediment and sequence onlap toward diapir in direction of arrows.
Figure 22. Downcut channel on seismic section.
LINE 244

Shotpoints

S 1 mile N

100

200

300

400

STREAM CHANNEL
downcutting into a lower sequence. A channel width of 4 kilometers (13000 feet) is indicated in Figure 23. The channel appears to have been meandering due to the presence of accretionary sediments denoted by the diagonal stratal reflections within the channel.

Figure 24 illustrates a shell bank on the top of a diapir. The hard surface of the shell bank is indicated by the five multiple reflections noted throughout the section. The chaotic or reflection free zone typically beneath diapirs is seen in Figures 24 and 19. A gas seep has been interpreted for the occurrence noted in Figure 25. High frequency reflectors appeared in the water column above the feature due to the release of gas. This feature was seen in an area between two diapirs, one a northern province diapir, the other a shelf edge diapir. Faulting was not noted in the sediment column below the feature, although such faulting could have been masked in the chaotic reflection pattern.

Faults

Faulting was noted as a prevalent feature of the study area (Figure 26). The preponderance of
Figure 23. Meandering channel on seismic section.
Shotpoints

VE12x

STREAM CHANNEL
Figure 24. Shell bank and multiple reflections of hard sediment surface.
Figure 25. Gas seep on seismic section. Seep located between a shelf edge diapir and a more landward diapir. Chaotic reflections present below feature.
LINE 780

Shotpoints

VE 17x

GAS SEEP
Figure 26. Fault map of study area.
north-south lines in comparison to east-west lines may have skewed the representation of faults toward an east-west trend. Growth faults were located near the shelf edge, extended tens of kilometers, and were arcuate in outline. Growth faults paralleled the trend of the shelf break. The down to the basin throw of the growth faults allowed expansion of sediment section to 25% (Figure 27). Maximum offset of strata was 30 meters (100 feet). Growth faults account for approximately one third of the faults mapped. Both growth faults and faults associated with diapirs exhibited sediment surface involvement in the faulting process (Figure 28). Faults scarps to 30 meters (100 feet) were apparent. Faulting associated with diapirs did not show a radial pattern. This fact may have been due to bias caused by interpretation and/or grid pattern. The faults located near diapirs were more local in extent and indicated a complex pattern of downthrown and upthrown segments.

Reflection Terminations

Reflection terminations were used to distinguish seismic sequences. The upper boundary of several sequences was indicated by toplap. Figure 29 shows toplap at an angular unconformity.
Figure 27. Seismic section of growth fault. Fault displacement 30 meters (100 feet); expansion of section is 25%.
Figure 28. Fault scarp with 30 meters (100 feet) of sediment displacement.
Figure 29. Angular unconformity near salt dome
outer continental shelf/upper slope.
LINE 104

Shotpoints

VE 25

ANGULAR UNCONFORMITY
Note the ringing character of the boundary and the reflection termination into the ringing cycles. Toplap and concordant features at the upper boundary surface are depicted in Figure 30. The sigmoid clinoform character (Figure 31) of this sequence demonstrates internal convergence, toplap converging into parallel reflectors, and slightly hummocky parallel reflectors.

Lower boundaries of several strata were indicated by downlap and onlap. Stratal onlap is illustrated in Figure 32. The strata lap out against the inclined surface of the stratigraphically lower sequence with the chaotic character. Downlap is exhibited (Figure 33) at the lower boundary in a sequence seen below the sea floor multiple. The fact that sequence position is below the multiple may make this interpretation suspect.

Concordant reflection patterns are illustrated in Figure 34. The concordant features noted in most sequences were parallel reflectors (railroad pattern). Semi-transparent reflectors (broken railroad pattern) were noted in the uppermost sequence.

Figures 35 shows chaotic reflections. The diagonal-chaotic pattern suggested an interpretation of stream channels. The diagonal
Figure 30. Line drawing of sigmoid clinoform configuration depicting toplap and concordant features.
Figure 31. Sigmoid clinoform configuration on seismic section. Note the internal convergence, toplap, and parallel reflectors.
Figure 32. Stratal onlap on diapir surface (area of chaotic reflections).
Figure 33. Downlap at base of sequence. Reflections may terminate at a multiple reflector.
LINE 144

Shotpoints

S

1 mile

1 km

N

200

300

VE 15

VE 15

DOWNLAP
Figure 34. Parallel and semi-transparent concordant reflection configuration.
Figure 35. Chaotic reflection configuration suggestive of channels.
LINE 984

Shotpoints

CHAOTIC CHARACTER
reflections seemed to indicate stream accretion or
downcut into the sediment.

Seismic Sequences

Figures 36 (dip section) and 37 (strike section) present the 4 sequences interpreted for the study area. Sequences were designated by numbers 1 through 4 with sequence 1 at the top of the section and sequence 4, the lowermost interpreted sequence. The following paragraphs describe each unit from observations of boundaries, internal character, and sediment thickness patterns. A detailed interpretation for each sequence is presented in the next chapter.

**Sequence 1**

The uppermost sequence had semi-transparent and parallel reflectors in all parts of the study area (Figure 38). The internal character of the sequence did not exhibit lapout. The lower boundary was distinguished by acoustic contrast between this sequence and the one below it. The sequence was variable in sediment thickness. In the western area the true thickness may have been masked due to noise from the water-sediment interface. The isopach map (Figure 39) illustrates maximum
Figure 36. Seismic sequences in dip section.
Figure 37. Seismic section on strike section.
Figure 38. Seismic section illustrating Sequence 1.
Figure 39. Isopach map of Sequence 1.
SEQUENCE 1
ISOPACH MAP

Contour in meters ≥ 10

Diapir

Fault
sediment thickness in the northeast part of the study area. The sediment was seen to become thinner toward the shelf and over diapirs. The trough of the tertiary withdrawal synclines were local depositional sites. Sediment distribution indicated a decrease in sediment thickness away from the probable sediment source.

Sequence 2

The second sequence (Figure 40) was characterized by reflection terminations at the upper boundary (toplap) in the southern part off the study area (Figure 41). Elsewhere the upper boundary exhibited a parallel configuration. The lower boundary was distinguished by acoustic contrast between this sequence and the one below it.

The isopach map (Figure 42) exhibits a tremendous increase in sediment thickness at the area interpreted as the edge of the paleoshelf (southeast part of the study area, Figure 43). The paleoshelf edge was indicated by downslope increase in Sequence 2 sediment thickness and a chaotic reflection character of the paleoedge (Figure 444). Near the paleoshelf edge growth faults were prevalent in areas which exhibit increase in
Figure 40. Seismic section of Sequence 2.
Figure 41. Map of toplap configuration of Sequence 2.
Figure 43. Map of paleoshelf edge (obscured by diapirs in western section).
Figure 44. Section of paleoshelf edge. Note increase in sediment thickness above shelf edge in seaward (southern) direction.
sediment thickness. The western terminus of the edge was obscured by diapirs.

Locally, the sediment was seen to become thinner over diapirs and thicker in tertiary withdrawal synclines. Troughs between diapiric highs were depositional sites with a medium amount of sediment thickness.

**Sequence 3**

The third sequence (Figure 45) was characterized by toplap at the upper boundary in the southwest part of the study area (Figure 46). An area of diapirs disrupts the toplap configuration. Parallel reflectors were present in other areas. The lower boundary was distinguished by acoustic contrast between this sequence and the one below it. The isopach map (Figure 47) exhibits local thinning of sediments over diapirs and thickening of sediments in the tertiary withdrawal synclines. The sediment was seen to become thicker near the shelf break.

**Sequence 4**

The forth sequence (Figure 48) was characterized by broken parallel to chaotic-parallel reflectors over most of the study area.
Figure 45. Sequence 3 in seismic section.
Figure 46. Map of toplap configuration for Sequence 3.
Parallel reflectors

Diapir

TOP LAP

SEQUENCE 3
Figure 47. Isopach map of Sequence 3.
Figure 48. Seismic section showing Sequence 4.
LINE 064

Shotpoints

SEQUENCE 4
Figure 49 illustrates a local area of toplap. To the east of this area, the upper sequence boundary was not discernable from the water bottom multiple. The upper boundary was distinguished by acoustic contrast between this sequence and the one above it. Multiple reflections obscured most of the seismic data that might have allowed interpretation of sequence thickness and internal character.
Figure 49. Map of toplap configuration for Sequence 4.
Parallel reflectors

Obscured by multiple

TOPLAP
SEQUENCE 4
DISCUSSION

Sea Level Cycles and Seismic Sequences

Various authors have proposed dates for the occurrence of glacial eustatic sea level fluctuations for the Pleistocene (Thunnel, 1984; Picou, 1983; Beard, 1982; Lehneer, 1969). Two cycles of cold to warm periods were generally assumed to have occurred during the Wisconsin to Holocene time period (Figure 50). Since cores were not available to date the sediments for this study, we accept that two cycles of sea level change are adequate to explain our findings.

Lewis, 1984, as well as Sutter and Berryhill, 1985, demonstrated that upper Pleistocene sea level variations at the shelf edge could be determined from changes in sequence internal character. Relatively steep clinoform configuration of sequences seen on seismic section were interpreted to indicate shelf outbuilding and upbuilding during periods of low sea level. Between the progradational sequences, a concordant sequence of uniform thickness was interpreted as an intervening period of high sea level.

Lewis postulated that two cold to warm cycles were indicated for the upper Pleistocene sediments
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after Lewis, 1984
located offshore of Galveston. Seven seismic sequences were identified for the Galveston study. Sequences A, B, and C were interpreted to represent lobes of a delta. The delta was seen to prograde sediments over the shelf break during a low stand of sea level. Oblique clinoform reflection configurations were seen in sequences A, B, and C. Sequence D has been interpreted to represent a regime of sediment deposition which occurred during a period of rising sea level. Sequence D was characterized by uniform thickness and its boundaries were relatively concordant. Sequences E, F, and G suggested lobes of a delta that prograded to the shelf edge during a late Wisconsin low sea level stand (Figure 51). Modern transgressive sediments were recovered in cores but not identified on seismic section. The thin Holocene sediments in the Galveston study would have been below seismic resolution.

Berryhill (personal communication, 1983) indicated that two cold to warm cycles could be interpreted for upper Pleistocene sediments located at South Marsh Island. Seismic sections were interpreted to illustrate 4 sequences that represented an early Wisconsin low stand, a middle Wisconsin high stand, a late Wisconsin low stand,
Figure 51. Comparison of sigmoid and oblique clinoform configuration. (from Lewis, 1984).
Oblique Clinoforms from Lewis, 1984

Sigmoid Clinoforms This Study
and a modern high stand. Berryhill's data, which extended to High Island, allowed correlation from this study area to that of Lewis.

Interpretation of Sequences

Four sequences were defined and have been illustrated in previous chapters. Sequences were labeled 1 through 4, with Sequence 1 representing the youngest or uppermost of the sediment packages interpreted from seismic sections. Typically, Sequence 1 demonstrated thinning of sediments over diapirs and thickening of sediments in the tertiary withdrawal synclines described by Seni and Jackson (1983). The sequence thickened appreciably toward the probable sediment source (Figure 39). Sediment thinned near the shelf break.

The internal reflection pattern of Sequence 1 showed parallel to semi-transparent reflectors. Bouma (1983) described a similar reflection pattern which he interpreted as pelagic and/or hemipelagic sedimentation. The low amplitude character of the reflections suggested sediments of a uniform lithology. The reflectors of Sequence 1 were concordant with the upper boundary of Sequence 2. The internal character, pattern of sediment thickness, and stratigraphic position suggested
that this sequence represents Holocene deposition during a rising and high stand of sea level.

Sequence 2 presented a different pattern of sediment thickness. Sediment was thickest at the outer continental shelf and thinner toward the inner shelf. Sediment is thin to missing over diapirs. Similar to the reports of Lewis (1984) and Suter (1985), this sequence also contained channels. Near the paleoshelf edge the upper boundary of this sequence exhibited toplap reflection terminations. The sequence illustrated concordant high amplitude parallel reflectors in areas more distant from the shelf edge. The continuity and amplitude of the reflectors suggested a lithology of a mixed sand and shale composition.

Sequence 2 was the only one of the four to exhibit clinoform reflection terminations. Figure 52 shows the reflection pattern. The steep clinoforms described by Lewis were not seen (Figure 51). The sigmoid clinoform pattern of Sequence 2 represented a lower energy depositional environment than that of oblique clinoforms (Mitchum, 1977). Lehner (1969) and Suter (1985) indicated deltaic environments were characterized by clinoform reflection configurations.
Figure 52. Sequence 2 on seismic section.
The lower boundary of Sequence 2 (Figure 53) suggested characteristics of the description of Type 2 unconformities by Vail, et al., 1983. Onlap was not indicated on sections, but may have been landward in a more updip northern position out of the study area. Type 2 unconformities were stated to indicate subsidence at the shelf edge to be greater than the subsidence of the inner shelf and onlap to be located updip of the shelf edge. Type 2 unconformities were stated to characterize periods of slowly falling sea level.

The lower boundary of Sequence 2 was interpreted as a conformity portion correlative to a Type 2 unconformity updip. The sequence was seen to thin in its northern reaches and was assumed to onlap and pinch out at a subaereal unconformity. The unconformity surface would be located in the area where the rate of sea level fall equalled the rate of shelf subsidence.

The thickness pattern, presence of channels, reflection continuity and configuration, and stratigraphic position suggested that Sequence 2 was deposited during a slow fall of sea level or a low stillstand of sea level.

Sequence 3 (Figure 54) showed patterns similar to Sequence 1. Thin sediments were present over
Figure 53. (a) Diagram of Type 2 unconformity (from Vail et al., 1983). (b) Sequence 2 sigmoid clinoform pattern.
UNCONFORMITY SUBAERIAL (TYPE 2)

EUSTATIC SEA LEVEL

SLOW FALL
LESS THAN RATE OF SUBSIDENCE AT SHELF EDGE

after Vail et al., 1983

TYPE 2 UNCONFORMITY
Figure 54. Sequence 3.
LINE 064

Shotpoints

Milliseconds

VE 17x

SEQUENCE 3
diapirs and thicker sediments were present in
tertiary withdrawal synclines and toward the
sediment source. Although the sediment at thickness at
the shelf break was thicker than sediments of
Sequence 1, the sediment was much thinner in this
area than that of Sequence 2. Sediments of this
sequence were more uniform in thickness, diapiric
influence considered, than the sediment of Sequence
2.

Like Sequence 1, Sequence 3 exhibited a high
amplitude sequence boundary reflection. Beard
(1982) stated that these high amplitude events were
due to the acoustic contrast between sequences.
High density sediment was deposited during cold
periods and low density sediment was deposited
during warm periods. The density contrast affects
the seismic character at sequence boundaries.

Very low angle (less than 0.25 degree) toplap
was indicated at the upper sequence boundary
(Figure 54). Toplap in this instance may have been
a function of deposition on a slowly subsiding
shelf. Clinoform reflection configurations were
not seen in the sequence. The stratal reflections
were continuous and amplitudes seemed high.

The relative concordant character of the
sequence boundary and stratigraphic position
suggested deposition during a stillstand of high sea level. The absence of channels may lend credence to this interpretation.

The chaotic character (Figure 48) at the upper boundary of Sequence 4 suggested the presence of channels. The internal character of Sequence 4 was obscured in the eastern part of the study area by the water-sediment multiple. Except for a small area of toplap and downlap, Sequence 4 is either chaotic to chaotic-parallel in character. Due to the presence of channels, Sequence 4 was interpreted as being deposited during a low stand of sea level.

Sequence 4 does not show a clinoform character. A clinoform pattern would be expected downslope (basinward) of the chaotic-parallel character seen on the seismic records. Since the presumed location of clinoform configuration for Sequence 4 was basinward of the clinoform pattern of Sequence 2, sea level was assumed to have been lower during the deposition of Sequence 4 than during deposition of Sequence 2.

The sequences described in this study correlate with those reported by Lewis (1984). Sequence 4, interpreted as one deposited during a low stand of sea level, correlates to Sequence A,
B, and C of Lewis. These sequences were interpreted as deltaic lobes deposited at the shelf edge during a low sea level stand. Sequence D of Lewis related to Sequence 3; both were seen to correspond to deposition during a high stand of sea level. Sequence 2 correlated to Sequence E, F, , and G of Lewis. These sequences were interpreted as deltaic lobes deposited at the shelf edge during a late Wisconsin low sea level stand. Sequence 2 was interpreted to have also been deposited at the shelf edge during a low stand of sea level. Lewis did not report a Holocene sequence on seismic records. Sequence 1 was the expression of Holocene deposition in this study area. The more eastern location for this study would be expected to exhibit a more defined and thicker Holocene sediment if the modern Mississippi River were the sediment source. The sequence interpreted as Holocene was seen to thin progressively to the west.

Diapirs, Channels, and Faults

Two provinces of structural style were indicated for diapirs present in the study area. Diapirs in the northern province were separate and did not influence sediment surface topography.
Growth faults were rarely seen in this province. Diapirs in the shelf edge province seemed connected and formed areas of uplift that affected sediment surface topography. Local areas of growth faulting were present.

Diapirs located in the northern area were seen to form anticlinal structures due to the uplift of sediments (Figure 20). The sediment surface topography near the diapir did not appear to have been altered. Intense local faulting was associated with the diapir uplift. These faults were difficult to trace from section to section. Diapirs of the northern province seemed to have dammed recent sediments updip of the diapir location (Figure 55).

In the northern province, the sediments seen lower in section indicated little change in sediment thickness in the areas of uplift. The upper two sequences seemed to pinch out over the diapirs. Above the diapir crest, Sequence 2 was absent; ringing at the sediment-water interface obscured the thickness of Sequence 1. Sequence 2 may have been eroded during the late Wisconsin low stand of sea level. Suter and Berryhill (1985) indicated that erosion of surface sediments above diapirs occurred during low stands of sea level. The absence or thinning of the more recent sequences...
Figure 55. Sediment dammed behind northern province diapir.
Sediment of Sequence 1 Dammed Behind Diapir
above the structure suggested erosion had indeed occurred.

The channels seen in Sequence 2 were present only in the northern province. Channels generally were seen to trend around the area of diapir uplift. A channel which downcut into Sequence 3 was located in the eastern part of the study area. Wide meandering channels have been interpreted for the central part of the study area, and smaller distributary channels were located in the west. If the channel was downcut as much as seemed to be indicated, then stream flow may have been from east to west.

Diapirs located at the shelf edge province disrupted the sediment thickness patterns (see isopach maps). The seismic sections indicated thinning of sequences near diapirs. These sediments were thicker in the tertiary withdrawal synclines and thin and/or pinchout at the diapir crest (Figure 19). This pattern suggested deposition of sediments contemporaneous with diapir uplift. Above the crest of the diapir, sediments may have been the transgressive sediments of Sequence 1. These sediments could not be accurately interpreted due to ringing at the sediment-water interface. Both growth faults and faults associated with
diapirs were present in this province. A true radial pattern of faults was not indicated for either province.

The diapirs at the shelf edge province formed local zones characterized by uplifts and depressions in the sediment surface. As described by Lehner (1969), the trough between the diapirs were loci of deposition (Figure 56). Growth faults were associated with these local areas of deposition. The growth faults seemed initiated by the diapirs and are accentuated by sedimentation and salt withdrawal. Salt withdrawal allowed formation of the tertiary synclines. The sink formed a depocenter and sediment loading initiated faulting. Subsequent sedimentation augmented the growth fault.

Growth faults were located in the eastern part of the study area were not associated with diapirs. In this area growth faulting was caused by sediment loading.

The two provinces were similar to those reported by Woodward (1973). The northern diapirs of this study corresponded to Woodward's isolated diapirs of the inner shelf. The semi-continuous uplift zone of Woodward was similar to the broad pattern of diapir uplift and depression seen at the
Figure 56. Sediment trough in depression between diapirs.
Contour  
Fault  
Diapir  
Trough outline  

DEPRESSIONS
outer shelf.

The outer shelf diapir province correlated with the slope diapirs of Lewis (1984). The isolated diapirs Lewis described for the inner shelf and shelf edge related to the diapirs located in this study's northern province.
CONCLUSION

1. Using single channel (airgun) seismic reflection data from the northcentral Gulf of Mexico, four seismic sequences were defined using the technique developed by Mitchum, et al. (1977). The interpretation involved sequence discrimination based on boundary character, internal stratatal configuration, and lateral sequence and stratatal continuity. The uppermost sequence, Sequence 1, represents Holocene transgressive deposition. Sequence 2 was a late Wisconsin glacial period sequence deposited during a low stand of sea level. Sequence 3 represented deposition during a middle Wisconsin interstadial period. The fourth sequence represented an early Wisconsin glacial period sequence, the sediment deposited when sea level was lower than during the late Wisconsin glacial period.

2. Diapirs influenced sedimentation patterns. Tertiary withdrawal synclines, as described by Seni and Jackson (1983), were the sites of local deposition. Growth faulting may have been initiated at these local depocenters. Diapirs routed streams around their uplifted areas. These
uplifted areas were eroded during periods of low sea level. Troughs between diapir uplifts were conduits for sediment transport. Diapirs dammed sediment behind areas of uplift if troughs were not present to conduct sediment from the area. Diapirs near the outer continental shelf demonstrated uplift contemporaneous with sediment deposition. The local faulting associated with diapirs was not correlatable from line to line. Based on the style of diapirs, presence of channels, fault patterns, and sediment thickness two diapiric provinces were defined.

3. Growth faults were most active in the extreme eastern part of the study area. This area had growth faults which extended from section to section and could be correlated for kilometers. Similar to the depocenters associated with diapirs, the eastern depocenter may have initiated growth faulting due to sediment loading. Growth faults were less influential on sediment deposition in the western portion of the study area.
Mitchum, Vail, and Thompson (1977) defined a depositional sequence as "a stratigraphic unit composed of a relatively conformable succession of genetically related strata bounded at its top and base by unconformities or their correlative conformities". A depositional sequence can best be recognized by its reflection pattern on seismic sections (Beard, 1982). A depositional sequence has been defined as a seismic sequence when viewed on seismic sections.

Approximatively, and within a geologic time frame, strata within a depositional (seismic) sequence are time synchronous. Sheriff (1977) stated that reflections typically follow depositional time surfaces rather than facies boundaries. Reflections of an unconformity surface may have been from a "time variable" boundary, but the strata below the boundary are older and the strata above the boundary are younger.

The boundaries of a sequence can be found by determining discordant features of strata. Discordant relations are based on their lack of parallelism in relation to bounding strata. Reflection terminations are the criterion for
establishing discordant features. Reflections can terminate at either the upper or lower sequence boundary.

Baselap has been defined as reflection termination or lapout at the lower sequence boundary. From Mitchum, et al. (1977): "onlap is baselap in which an initially horizontal stratum laps out against an initially inclined surface, or in which an initially inclined stratum laps out updip against a surface of greater initial inclination; downlap is baselap in which an initially inclined stratum terminates downdip against an initially horizontal or inclined surface; erosional truncation is the lateral termination of strata by erosion along the unconformity surface; toplap is lapout at the upper boundary of a depositional sequence".

Erosional truncation and toplap exemplify reflection terminations or lapouts at the upper surface boundary (Figure 57). Toplap represents a sequence boundary exhibiting little or no erosion. Toplap results from a relative falling or stillstand of sea level. At the site of deposition, sea level is too low to permit strata to extend further updip.

Internal convergence has been defined as
Figure 57. Seismic stratigraphic reflection terminations. (from Mitchumum, et al., 1977).
SEISMIC STRATIGRAPHIC REFLECTION TERMINATIONS

ONLAP

OFFLAP

TOPLAP

DOWNLAP

INTERNAL DIVERGENCE

(UNDERLYING UNCONFORMITY)

(UNDERLYING UNCONFORMITY)

TRUNCATION

after Mitchum et al., 1977
stratal surfaces which terminated within a sequence. Reflection termination is due to stratal thinning below seismic resolution. Vaill, Thompson, and Mitchum (1977) suggested one half wavelength as the resolution limit. Sheriff (1977) stated that seismic resolution is about one forth to one eighth wavelength. Sheriff discriminated minor changes of reflection amplitude.

Internal convergence can be confused with terminations along a sequence boundary. Strong reflectors can produce ringing at a sequence boundary. The ringing is similar to the pattern seen at the water-sediment interface. Bécard (1982) described two or more cycles of reflection below strong reflectors between sequences of highly contrasting seismic properties. Mitchum, Vail and Sangree (1977) noted "follow cycles" beneath principle reflectors. The ringing at strong reflectors can mask seismic data. Internal convergence can be interpreted to be an actual lapout if the termination is at a ringing cycle. Lapout can be interpreted as internal convergence due to the masking of the actual sequence boundary. Due to ringing effects, the upper boundary of the sequence is more difficult to interpret.

Sequences can have concordant surfaces which
appear as a series of parallel reflectors or stratal surfaces. Terminations are not present within the sequence boundaries. Concordant surfaces alone cannot be used as a basis for distinguishing one sequence from another. The area of discordance within a sequence can be traced into areas in which the strata appear parallel (Figure 58).

Internal Features of Seismic Sequences

Seismic sequences are also characterized by an internal form and reflection configuration. Internal reflection variations have been described and their depositional setting interpreted by Mitchum, Vail, and Sangree, (1977); Sangree and Widmer, (1977); Stuart and Caughey, (1977); Brown and Fisher, (1977 and 1982); Bouma, Stelting, and Feely, (1983); and Suter and Berryhill, (1985). Parallel reflectors can be evenly parallel, wavey, and subparallel (Figure 59). Parallel configurations suggest uniform rates of deposition. Parallel reflectors with high amplitude and high continuity (railroad pattern) suggest strata containing high seismic contrast, interbedded sand and shale; parallel reflectors with low amplitude suggest strata of low contrast, one of singular lithology. Low amplitude or semi-transparent
Figure 58. Discordant relationship of strata to depositional sequence boundaries. (from Mitchum, et al., 1977).
UPPER BOUNDARY

1. EROSIONAL TRUNCATION
   A.

2. TOPLAP

3. CONCORDANCE

LOWER BOUNDARY

1. ONLAP
   B. BASELAP

2. DOWNLAP

3. CONCORDANCE

after Mitchum et al., 1977
Figure 59. Parallel, subparallel, and divergent seismic reflection configurations. (from Mitchum, et al., 1977).
after Mitchum et al., 1977.
reflectors may contain coarser clastics than high amplitude reflectors (Bouma, et al., 19983). Divergent parallel reflectors are characterized by internal convergence and exhibit a wedge-shaped form. Divergent configurations suggest lateral variation in rate of deposition or contemporaneous depositional surface tilting and sedimentation. Parallel reflectors suggest hemipelagic sedimentation on shelfal areas.

A prograding depositional sequence is indicated by clinoform reflection configurations (Figure 60). A sigmoid (lazy s shape) pattern in dip section has a thin concordant upper segment, a concordant to gently downlapping lower segment, and a thicker more steeply dipping (less than 1 degree) middle segment. On sections parallel to depositional strike, the reflections are parallel and concordant. Sigmoid configurations suggest a relatively low sediment supply, rapid basin subsidence, and/or rapid rise in sea level. Sigmoid facies are often associated with and may grade into an oblique clinoform pattern.

An oblique configuration along dip section exhibits toplap at the upper segment and downlap at the lower segment. The dip (to 10 degrees) of the middle segment foreset is characteristically
Figure 60. Clinoform reflection configurations. (from Sangree and Widmer, 1977).
SHELF-MARGIN SEISMIC FACIES TYPES

SIGMOID-PROGRADATIONAL

OBLIQUE-PROGRADATIONAL

after Sangree and Widmer, 1977
higher than the sigmoid configuration. Similar to the sigmoid configuration, the middle segment is thicker than the limb segments; oblique mid-sections usually are thicker than sigmoid pattern mid-segments. On strike section, the reflections may appear parallel, low angle sigmoid or oblique, and/or mounded (Figure 61). Oblique patterns suggest relatively high sediment supply, slow basin subsidence, and/or a stillstand in sea level. The foreset segment of both clinoform patterns suggest an outbuilding of sediments. A clinoform configuration suggests deltaic sedimentation on a continental shelf or prograding slope.

A chaotic configuration exhibits discontinuous and disordered reflection patterns. The upper boundary of sequences with chaotic patterns may be mounded. Chaotic patterns suggest that initially continuous strata have been deformed to disrupt continuity. Deposits from turbidity currents may also exhibit chaotic patterns. The chaotic configuration can be so disordered that interpretation is not possible.

Relative Sea Level

Vail, Mitchum, and Thompson (1977) stated that a relative rise of sea level is indicated by
Figure 61. Mounded reflection configuration in strike section, oblique reflection configuration in dip section. (from Brown and Fisher, 1982).
after Brown and Fisher, 1982
coastal onlap. Coastal onlap is the prooressive landward onlap of sequences. A relativeree standstill or apparent constant sea level position can be determined by toplap. Each stratum laps out in a landward direction at the top of the sequence. A relative fall in sea level is indicated by a downward shift of coastal onlap (Figure 62). Vail, et al. described sea level variations as two stages of a cycle, a gradual relative rise and a rapid relative fall. The relative fall in sea level produces unconformities.

The relative height of sea level is a complicated combination of effects from subsidence, uplift, and sedimentation rate along with eustatic effects. Sea level change can be determined from other events reflected on the seismic record. A transgressive sediment sequence overlying stream beds and/or a deltaic sequence indicates a sea level rise or subsidence. Erosion of continental shelf and deltaic sedimentation at the shelf edge may indicate sea level fall or uplift. Stillstands can occur with constant sea level position, rising sea level, or falling sea level. Seismic evidence must be considered in light of other evidence obtainable.
Figure 62. Relative rise, fall, and stillstand of sea level. (from Vail, et al., 1977)
LOW TERRIGENOUS INFLUX — TRANSGRESSION

HIGH TERRIGENOUS INFLUX — REGRESSION

BALANCED TERRIGENOUS INFLUX — STATIONARY SHORELINE

DOWNWARD SHIFT IN COASTAL ONLAP INDICATES RAPID FALL

after Vail et al., 1977
Seismic Sequence Analysis

Mitchum, et al. (1977) described seismic sequence analysis as outlining the boundary of the seismic sequence. Reflection terminations establish the sequence boundary. Reflections do not terminate in concordant reflection areas; parallel reflection configuration will be treated in a later procedure. The part of the seismic record of interest is the area containing a discordant relation such as a clinoform configuration. Care must be taken to recognize internal convergence and apparent termination of internal convergence at ringing reflection boundaries. Most clinoform features contain downlapping strata at the lower boundary. The lower boundary is also less likely to be affected by ringing. The lower boundary may be an easier sequence boundary to recognize.

The procedure for onlapping strata is similar. The strata reflections terminate (downlap) against an inclined surface. The different inclinations across the sequence boundary are similar to an angular unconformity. The boundary surface may not necessarily be an erosive feature.

Erosional truncation is a relatively simple to recognize on seismic section. High seismic contrast is characteristic of erosional boundary surfaces.
The seismic signal exhibits high amplitude and continuity along erosional truncations. Lapout or reflection termination is seen at this upper sequence boundary. Toplap can define upper boundary surface for areas of oblique reflection patterns as well as areas characterized by erosional truncation.

Toplap is not present in sigmoid reflection patterns. The middle segment of sigmoid pattern grades into a concordant upper segment. The concordant features are traced away from the area of discordance. If the seismic contrast is sufficient, a characteristic ringing or follow cycle can be determined for the sequence. The ringing pattern can easily be traced in the concordant areas.

Every sequence is traced from areas of discordant features (toplap, downlap, and onlap) extending through to include the area with concordant characteristics. The procedure is repeated for each seismic line. A loop can be tied within a grid of lines. The loop may confirm accuracy in tracing of sequence boundaries. Lack of correlation requires redefinition of sequence boundaries to resolve mismatch until a reasonable correlation can be achieved.
A part of the previous procedure involved the first step of seismic facies analysis, describing the character of internal reflections within the sequence boundary. Patterns of internal reflections indicate a seismic facies. Stratal geometry, reflection continuity and thickness patterns which vary over the seismic section can be used to refine the description of the seismic facies.

Each sequence is analysed to determine its seismic facies. The seismic facies change can be compared for the sequence on any one record and/or the facies change can be compared between records. A facies map is usually constructed as are sediment thickness maps. The sediment thickness maps can be either isochrons or isopachs. Mapping can include other features that characterize the study area. Structure such as diapirs and faults due to diapirs and/or growth faults can also be mapped.

Paleogeography and geologic history can be deduced from maps of seismic facies change. Environment of deposition, sediment transport direction, and sea level change can be estimated. The most accurate interpretations include maximum utilization of collateral data such as information from well logs and paleontologic investigations.


Vail, P. R., J. Hardenbol, and R. G. Todd, 1983, Jurassic unconformities chronostratigraphy and biostratigraphy: Reprint from AAPG Memoir on regional unconformities, 31pp.


