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Salt and slope tectonics offshore Louisiana

Wu, Shengyu, Ph.D.
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SALT AND SLOPE TECTONICS
OFFSHORE LOUISIANA

by
Shengyu Wu

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APPROVED, THESIS COMMITTEE

D. W. Bally
Albert W. Bally, Director
Harry Carothers Wiess Professor of
Geology and Geophysics

Dale S. Sawyer
Associate Professor of Geology and
Geophysics

John B. Anderson
Professor of Geology and Geophysics

B. Ramaswamy
Assistant Professor of Mechanical
Engineering and Materials Science

Houston, Texas
May, 1993
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Abstract

Mid-Jurassic salt was deposited on a smooth regional unconformity. The salt thins toward the south to pinch out near a roughly E-W trending transitional-oceanic crust boundary. Four episodes of Meso-Cenozoic tectonics can be differentiated as follows.

1. From its mid-Jurassic deposition to the mid-Cretaceous, salt was deformed perennially by sediment loading. As a result, peripheral fault systems, salt domes, salt anticlines, salt massifs, salt rollers and local growth structures were formed. Much of the salt was pushed toward the basin by a sediment load and concentrated near the present slope. Some salt had already formed small scale allochthonous salt bodies. An extensive primary weld formed under the Early Cretaceous platform and upper slope as salt was squeezed out.

2. During a significant period of sediment starvation, between mid-Cretaceous (Turonian) and mid-Oligocene time, previously formed salt structures were stabilized.

3. From mid-Oligocene to early Middle Miocene time, early salt structures were reactivated by rapid sediment loading. By middle Middle Miocene time, large diapiric salt ridges, walls and stocks formed in response to increased sediment loading. The growing salt structures, driven by buoyancy and differential loading, caused the downslope displacement of the overlying Mesozoic-Middle Miocene section. This lateral displacement is transmitted downslope, decoupling the Mesozoic-Middle Miocene section over the salt and toward the basinward pinchout of salt. Thus strains, not accommodated by the primary salt withdrawal basins, were transmitted to and concentrated along the basinward edge of salt to form the Mississippi Fan Fold Belt. Shortening in the Mississippi
Fan Fold Belt ceased by Late Miocene as the salt walls and stocks had made their way up through the overburden and began to emplace in the less dense sediments of the slope to form allochthonous salt structures. During and following the formation of the Mississippi Fan Fold Belt and updip from the fold belt, large primary withdrawal basins, along with landward and seaward dipping and local growth fault systems, and primary welds were formed due to massive salt withdrawal at the base of the Meso-Cenozoic overburden. Inclined and subvertical secondary welds were also formed as feeder stocks or walls thinned to accommodate some of the updip extension in the primary withdrawal basins.

(4) From the Late Miocene to present, large-scale asymmetric primary allochthonous salt sheets continued to form and advance downslope. As sedimentation continued during the primary allochthonous salt development, secondary salt withdrawal basins with associated basinward and landward dipping growth faults, tertiary welds, local folds and reverse faults formed over the deformed allochthonous salt. The secondary allochthonous salt structures and tertiary withdrawal basins and later welds evolved as the primary allochthonous salt was deformed by the Plio-Pleistocene sedimentation in the Green Canyon area. Some of the salt cores of the Mississippi Fan Fold Belt pierced through the overburden to form allochthonous salt bodies, e.g. Green Knoll. The primary and secondary allochthonous salt structures have strong expressions on the sea floor.
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Table of Contents

Abstract .................................................................................................................... ii
Acknowledgments ................................................................................................... iv
Table of Contents ................................................................................................... vii
List of Illustrations ................................................................................................. xiii
  List of figures ....................................................................................................... xiii
  List of tables ....................................................................................................... xxii
  List of plates ........................................................................................................ xxiii
  List of maps ......................................................................................................... xxiv

Chapter One

Introduction ............................................................................................................. 1
  1.1. Review .......................................................................................................... 1
  1.2. Objectives .................................................................................................... 2
  1.3. Seismic and well data ................................................................................... 2
  1.4. Overview ..................................................................................................... 5
  1.5. Approach ..................................................................................................... 15

Chapter Two

Sequence Stratigraphy ........................................................................................... 16
  2.1. Sequence stratigraphic interpretation of well information ....................... 16
  2.2. Sequence stratigraphic correlation of regional seismic profiles .............. 22
  2.3. Sequence stratigraphic framework .............................................................. 32
  2.4. Pattern of sediment distribution ................................................................ 33
Chapter Three
Configuration of the Basement and Distribution of Mid-Jurassic Salt ............... 39

Chapter Four
Pre-Mid-Cretaceous Sedimentation and Salt Movements .......................... 51
4.1. Pre-mid-Cretaceous deformation on the shelf .................................. 51
4.2. Pre-mid-Cretaceous deformation on the slope .................................. 57
4.3. Mid-Cretaceous allochthonous salt ................................................. 58
4.4. Mid-Cretaceous salt distribution ...................................................... 68
4.5. Discussions and summary ............................................................... 69

Chapter Five
Mid-Cretaceous to Mid-Oligocene Stabilization of Structures ..................... 71

Chapter Six
Neogene Development of Allochthonous Salt ......................................... 73
6.1. Distribution and morphology ......................................................... 74
6.2. Reactivation of pre-existing salt structures ....................................... 76
6.3. Active diapirism and related structures .......................................... 77
6.4. Spreading of allochthonous salt and development of related structures .... 85
6.5. Secondary allochthonous salt structures ......................................... 86
6.6. Summary ........................................................................... 96

Chapter Seven
Mississippi Fan Fold Belt ...................................................................... 97
7.1. Location and extent .................................................................. 97
Chapter Eight

Models and Relationship Between Salt, Extensional and Contractional Tectonics on the Continental Slope

8.1. Models of the evolution of allochthonous salt sheets from previous study

8.2. Models of salt diapirism

8.3. Models of salt deformation in the northeastern Gulf of Mexico

8.4. Relationship with salt movements and extensional systems

8.5. Mechanism of initiation and cessation of shortening in the Mississippi Fan Fold Belt

8.5.1 Time and space relationship between extension and contraction

8.5.2. Models for the development of the Mississippi Fan Fold Belt

8.6. Summary

Chapter Nine

Sub-Allochthonous Salt Structures

9.1. Salt structures

9.2. Extensional systems

9.3. Contractional systems

9.4. Summary
Chapter Ten

Supra-Allochthonous-Salt Structures ................................................................. 165
  10.1. Secondary allochthonous salt structures ............................................... 166
  10.2. Extensional systems ................................................................. 166
  10.3. Contractional systems ............................................................... 170
  10.4. Summary ......................................................................................... 187

Chapter Eleven

Submarine Erosion ......................................................................................... 188
  11.1. Incision of submarine canyons ......................................................... 188
  11.2. Erosion related to turbid flow ......................................................... 188
  11.3. Erosion related to non-deposition due to starved sedimentation ...... 188
  11.4. Erosion of the Mississippi Fan Fold Belt and the Sigsbee Escarpment .. 192
  11.5. Summary ......................................................................................... 195

Chapter Twelve

Interaction of Salt Movements and Sedimentation ...................................... 196
  12.1. Pre-mid-Cretaceous ................................................................. 196
  12.2. Mid-Cretaceous to mid-Oligocene ..................................................... 197
  12.3. Mid-Oligocene to Lower Miocene ...................................................... 197
  12.4. Middle-Miocene ............................................................................ 198
  12.5. Upper Miocene .............................................................................. 199
  12.6. Pliocene ......................................................................................... 199
  12.7. Pleistocene to present .................................................................... 200
  12.8. Conclusion ...................................................................................... 200
Chapter Thirteen
Salt Tectonics of the Northern Gulf of Mexico and Shale Tectonics of Offshore Nigeria - Similarities and Contrasts ........................................ 201

13.1. Structural styles and evolution of the northwestern Gulf of Mexico .......... 201
  13.1.1. Salt structures ...................................................... 203
  13.1.2. Extensional systems ............................................... 204
  13.1.3. Perdido Fold Belt .................................................. 205
  13.1.4. Summary ............................................................ 206

13.2. Structural styles and evolution of the continental slope offshore Nigeria ................................................................. 207
  13.2.1. Shale structures ..................................................... 210
  13.2.2. Extensional systems ............................................... 210
  13.2.3. Toe Thrusts .......................................................... 211
  13.2.4. Summary ............................................................ 213

13.3. Discussions and conclusions ........................................... 214
  13.3.1. Tectonic setting .................................................... 214
  13.3.2. Salt versus shale structures ..................................... 216
  13.3.3. Extensional systems ............................................... 216
  13.3.4. Contractional systems .......................................... 217
  13.3.5. Conclusions ....................................................... 218

Chapter Fourteen
Meso-Cenozoic Evolution of the Northeastern Gulf of Mexico ......................... 220

14.1. Conclusions .................................................................. 224
14.2 Possibilities of simulating the Meso-Cenozoic tectonics using physical and numerical modeling .......................................................... 227

14.2.1. Reviews of physical modeling ........................................... 228

14.2.2. Reviews of numerical modeling ....................................... 229

14.2.3. Ideal modeling experiments and critical phenomena to be modeled ........................................................................ 230

Bibliography .................................................................................. 233

Appendix I - Glossary for Salt Tectonics ...................................... 245
List of Illustrations

List of figures

Chapter One

Figure 1-1 Location of the study area in the northeastern Gulf of Mexico and regional Texas transect.

Figure 1-2. Seismic data and well information data base used in the northeastern Gulf of Mexico.

Figure 1-3. Regional structural elements.

Figure 1-4. Location of regional profiles in Chapter One.

Figure 1-5a. Regional NE - SW trending seismic line drawing in time.

Figure 1-5b. Regional NE - SW trending seismic line drawing in depth.

Figure 1-6a. Regional NW - SE trending seismic line drawing in time.

Figure 1-6b. Regional NW - SE trending seismic line drawing in depth.

Figure 1-7. Tectonic provinces of the study area.

Chapter Two

Figure 2-1. Index map for seismic examples in Chapter Two.

Figure 2-2. Location of well controls and well-log transects.

Figure 2-3. Line drawings of regional seismic profiles from offshore Mississippi and Alabama (after Wu et al, 1990b).

Figure 2-4. Regional well-log transect I (after Wu, 1989)

Figure 2-5. Regional well-log transect II.

Figure 2-6. Main sequence stratigraphic surfaces, well controls, lithology, changes of coastal onlaps, and eustatic sea levels.

Figure 2-7a. An uninterpreted well-tie seismic section. (with mid-Cretaceous allochthonous salt)
Figure 2-7b. An interpreted well-tie seismic section.

Figure 2-8a. An uninterpreted well-tie seismic section with Mid-Cretaceous allochthonous salt and pseudo-clinoforms.

Figure 2-8b. An interpreted well-tie seismic section of 2-8a.

Figure 2-9a. An uninterpreted well-tie seismic section with a turtle structure.

Figure 2-9b. An interpreted well-tie seismic section of Figure 2-9a.

Figure 2-10. Location of Late Jurassic-Cenozoic depocenters, northwestern Gulf of Mexico (after Salvador, 1991a, 1991b, McFarlan and Menes, 1991, Sohl et al, 1991).

Figure 2-11. Meso-Cenozoic average thicknesses, interval velocities and rates of sedimentation for the key intervals in the northeastern Gulf of Mexico. The intervals are P (0-1.9 Ma), PLI (1.9-5.5 Ma), UM (5.5-10.5 Ma), MM (10.5-15.5 Ma), LMWO (15.5-30 Ma), MOMC (30-91.5 Ma), MCTS (91.5-150.5 Ma).

Chapter Three

Figure 3-1. Distribution salt structures and regional tectonic features in the Gulf of Mexico (Martin, 1978).

Figure 3-2. Distribution and relative thickness of mid-Jurassic Louann salt in the Gulf of Mexico (Salvador, 1987).

Figure 3-3a. Salt distribution and its relationship with oceanic crust (Salvador, 1991b).

Figure 3-3b. Basement configuration and its relationship with salt of the Gulf of Mexico (Buffler, 1989).

Figure 3-4. Index map for seismic examples in Chapter Three.

Figure 3-5a. An uninterpreted seismic example of base of salt to salt-free basement boundary.

Figure 3-5b. An interpreted seismic example of base of salt to salt-free basement boundary.
Chapter Four

Figure 4-1. Index map for seismic examples in Chapter Four.

Figure 4-2a. Lithofacies-paleogeographic map, Albian. (from Sohl et al, 1991)

Figure 4-2b. Lithofacies-paleogeographic map, middle Cenomanian through Turonian (from Sohl et al, 1991)

Figure 4-3a. An uninterpreted NE - SW seismic example of salt withdrawal from original salt bed.

Figure 4-3b. An interpreted NE - SW seismic example of salt withdrawal from original salt bed.

Figure 4-4a. An uninterpreted NW - SE seismic example of salt withdrawal from original salt bed.

Figure 4-4b. An interpreted NW - SE seismic example of salt withdrawal from original salt bed.

Figure 4-5a. An uninterpreted NW - SE seismic example of normal faults related to salt withdrawal from original salt bed.

Figure 4-5b. An interpreted NW - SE seismic example of normal faults related to salt withdrawal from original salt bed.

Figure 4-6a. An uninterpreted NW - SE seismic example of mid-Cretaceous allochthonous salt bodies.

Figure 4-6b. An interpreted NW - SE seismic example of mid-Cretaceous allochthonous salt bodies.

Figure 4-7. Development of pseudo-clinoforms (after Wu et al, 1990b).

Chapter Six

Figure 6-1. Index map for seismic examples in Chapter Six.

Figure 6-2a. An uninterpreted NW - SE seismic example of allochthonous salt sheet and associated growth faults.
Figure 6-2b. An interpreted NW - SE seismic example of allochthonous salt sheet and associated growth faults.

Figure 6-3a. Southward extension of Figure 6-2a.

Figure 6-3b. Southward extension of Figure 6-2b.

Figure 6-4a. An uninterpreted NE - SW seismic example of allochthonous salt sheet and associated salt withdrawal structures.

Figure 6-4b. An interpreted NE - SW seismic example of allochthonous salt sheet and associated salt withdrawal structures.

Figure 6-5a. An uninterpreted NE - SW seismic example of a well imaged allochthonous salt sheet.

Figure 6-5b. An interpreted NE - SW seismic example of a well imaged allochthonous salt sheet.

Figure 6-6a. An uninterpreted NW - SE seismic example of secondary allochthonous salt tongue and associated withdrawal structures.

Figure 6-6b. An interpreted NW - SE seismic example of secondary allochthonous salt tongue and associated withdrawal structures.

Figure 6-7a. An uninterpreted NW - SE seismic example of growth structures on both primary and secondary allochthonous salt bodies.

Figure 6-7b. An interpreted NW - SE seismic example of growth structures on both primary and secondary allochthonous salt bodies.

Chapter Seven

Figure 7-1. Index map for seismic examples in Chapter Seven.

Figure 7-2a. An uninterpreted NW - SE seismic example from the eastern part of the Mississippi Fan Fold Belt.

Figure 7-2b. An interpreted NW - SE seismic example from the eastern part of the Mississippi Fan Fold Belt.
Figure 7-3a. An uninterpreted NW - SE seismic example of the Mississippi Fan Fold Belt across well Atwater Valley Shell #1.

Figure 7-3b. An interpreted NW - SE seismic example of the Mississippi Fan Fold Belt across well Atwater Valley Shell #1.

Figure 7-4a. An uninterpreted NW - SE seismic example of double vergence reverse faults from the middle part of the Mississippi Fan Fold Belt.

Figure 7-4b. An interpreted NW - SE seismic example of double vergence reverse faults from the middle part of the Mississippi Fan Fold Belt.

Figure 7-5a. An uninterpreted NW - SE seismic example of a peneplaned thrust from the western part of the Mississippi Fan Fold Belt.

Figure 7-5b. An interpreted NW - SE seismic example of a peneplaned thrust from the western part of the Mississippi Fan Fold Belt.

Figure 7-6a. An uninterpreted NW - SE seismic example of landward verging reverse faults from the western end of the Mississippi Fan Fold Belt.

Figure 7-6b. An interpreted NW - SE seismic example of landward verging reverse faults from the western end of the Mississippi Fan Fold Belt.

Figure 7-7a. An uninterpreted NW - SE seismic example across Green Knoll.

Figure 7-7b. An interpreted NW - SE seismic example across Green Knoll.

Figure 7-8a. An uninterpreted NE - SW seismic example across the Green Knoll and associated fold.

Figure 7-8b. An interpreted NE - SW seismic example across the Green Knoll and associated fold.

Figure 7-9a. An uninterpreted NW - SE seismic example of allochthonous salt sheet and associated growth faults.

Figure 7-9b. An interpreted NW - SE seismic example of allochthonous salt sheet and associated growth faults.
Figure 7-10a. An uninterpreted NW - SE seismic example of fold and reverse faults basinward of Figure 7-9a.

Figure 7-10b. An interpreted NW - SE seismic example of fold and reverse faults basinward of Figure 7-9b.

Chapter Eight

Figure 8-1. Pre-mid-Cretaceous deformation on shelf and slope (after Wu et al, 1990b).

Figure 8-2. Evolutionary stages of allochthonous salt (from Wu et al, 1990b).

Figure 8-3. Development of allochthonous salt and related master down-to-the-basin growth fault (Wu et al, 1990b).

Figure 8-4. Schematic active and passive diapirism process (Jackson and Talbot, 1991).

Figure 8-5. Sequence of diapirism with thin-skinned extension (Vendeville and Jackson, 1992a).

Figure 8-6. Ductile deformation of viscous fluid overburden during diapirism (Jackson, Talbot, Cornelius, 1988).

Figure 8-7. Removal of overburden during diapirism by erosion (Nettleton, 1933).

Figure 8-8. Deformation of flexible brittle overburden during active diapirism. (Seni and Jackson, 1984, modified from Trusheim, 1960).

Figure 8-9. Fracture and fold patterns produced by asphalt dome which penetrated the mud surface (Parker and McDowell, 1955).

Figure 8-10. Compressional deformation produced by the intrusion of a rigid plug (Parker and McDowell, 1955).

Figure 8-11. Viscous fluid model showing the folded overburden in front of the rising salt structures (Model 5 of Talbot, 1992).

Figure 8-12. Effect of a frictional boundary on shortening.

Figure 8-13. A schematic model for the initiation and cessation of shortening in the Mississippi Fan Fold Belt by salt movements.
Chapter Nine

Figure 9-1. Index map for seismic examples in Chapter Nine.

Figure 9-2a. An uninterpreted NW - SE seismic example of subsalt salt-withdrawal structure across well Mississippi Canyon 211 Exxon #1.

Figure 9-2b. An interpreted NW - SE seismic example of subsalt salt-withdrawal structure.

Figure 9-3a. An uninterpreted NW - SE seismic example of salt-withdrawal structure.

Figure 9-3b. An interpreted NW - SE seismic example of salt-withdrawal structure.

Figure 9-4a. An uninterpreted NW - SE seismic example of salt-withdrawal structure across well Mississippi Canyon 730 Shell #1.

Figure 9-4b. An interpreted NW - SE seismic example of salt-withdrawal structure across well Mississippi Canyon 730 Shell #1.

Figure 9-5a. An uninterpreted NW - SE seismic example of subsalt fold and reverse fault.

Figure 9-5b. An interpreted NW - SE seismic example of subsalt fold and reverse fault.

Figure 9-6a. An uninterpreted NE - SW seismic example of subsalt fold and reverse fault perpendicular to Figure 9-4a.

Figure 9-6b. An interpreted NE - SW seismic example of subsalt fold and reverse fault perpendicular to Figure 9-4b.

Chapter Ten

Figure 10-1. Index map for seismic examples in Chapter Ten.

Figure 10-2a. An uninterpreted NW - SE seismic example of early supra-allochthonous-salt growth faults.

Figure 10-2b. An interpreted NW - SE seismic example of early supra-allochthonous-salt growth faults.

Figure 10-3a. An uninterpreted NW - SE seismic example of a well-developed supra-allochthonous-salt growth fault.
Figure 10-3b. An interpreted NW - SE seismic example of a well-developed supra-allochthonous-salt growth fault.

Figure 10-4a. An uninterpreted NW - SE seismic example of well-developed supra-allochthonous-salt growth faults and welds.

Figure 10-4b. An interpreted NW - SE seismic example of well-developed supra-allochthonous-salt growth faults and welds.

Figure 10-5a. An uninterpreted NW - SE seismic example of supra-allochthonous-salt welds perpendicular to Figure 10-3a.

Figure 10-5b. An interpreted NW - SE seismic example of supra-allochthonous-salt welds perpendicular to Figure 10-3b.

Figure 10-6a. An uninterpreted NW - SE seismic example of a deep and well-developed tertiary weld.

Figure 10-6b. An interpreted NW - SE seismic example of a deep and well-developed tertiary weld.

Figure 10-7a. An uninterpreted NW - SE seismic example of supra-allochthonous-salt growth and reverse faults.

Figure 10-7b. An interpreted NW - SE seismic example of supra-allochthonous-salt growth and reverse faults.

Figure 10-8a. An uninterpreted NE - SW seismic example of a supra-allochthonous-salt weld perpendicular to Figure 10-6a.

Figure 10-8b. An interpreted NE - SW seismic example of a supra-allochthonous-salt weld perpendicular to Figure 10-6b.

Figure 10-9. Seismic example of reverse faults over a weld formed by advancing allochthonous salt sheet (after Huber, 1989).

Figure 10-10. Reconstruction of Jolliet Field thrust fault (from Cook and D'Onfro, 1991).
Chapter Eleven

Figure 11-1. Index map for seismic examples in Chapter Eleven.

Figure 11-2a. An uninterpreted NE - SW seismic example of submarine canyon.

Figure 11-2b. An interpreted NE - SW seismic example of submarine canyon.

Figure 11-3a. An uninterpreted NW - SE seismic example of submarine erosion at Sigsbee Scarp and Mississippi Fan Fold Belt.

Figure 11-3b. An interpreted NW - SE seismic example of submarine erosion at Sigsbee Scarp and Mississippi Fan Fold Belt.

Chapter Thirteen

Figure 13-1. Regional tectonic elements of the northern Gulf of Mexico and the study area.

Figure 13-2. Regional structural elements of the Niger Delta and location of seismic profiles.

Figure 13-3. Growth faults on mobile shale on the shelf offshore Nigeria (After Knox and Omatsola, 1989).

Figure 13-4. Conceptual model for the development of depobelts and shale structures (from Knox and Omatsola, 1989).

Chapter Fourteen

Figure 14-1. Summary of regional depocenters and its relationship with salt structures, extensional and compressional systems of the northern Gulf of Mexico.

Figure 14-2. Schematic Mesozoic-Cenozoic structural evolutionary stages of the northeastern Gulf of Mexico.
List of tables

Table 1-1 Interval velocities for depth conversion.

Table 1-2 Major Meso-Cenozoic tectonic events in the northeastern Gulf of Mexico. The crustal types of the basement are adapted from Buffett (1989) and Salvador (1991b).

Table 3-1 Major Meso-Cenozoic tectonic events in the northeastern Gulf of Mexico and the subjects discussed in Chapter Three. The crustal types of the basement are adapted from Buffett (1989) and Salvador (1991b).

Table 4-1 Major Meso-Cenozoic tectonic events in the northeastern Gulf of Mexico and the subjects discussed in Chapter Four. The crustal types of the basement are adapted from Buffett (1989) and Salvador (1991b).

Table 5-1 Major Meso-Cenozoic tectonic events in the northeastern Gulf of Mexico and the subjects discussed in Chapter Five. The crustal types of the basement are adapted from Buffett (1989) and Salvador (1991b).

Table 6-1 Major Meso-Cenozoic tectonic events in the northeastern Gulf of Mexico and the subjects discussed in Chapter Six. The crustal types of the basement are adapted from Buffett (1989) and Salvador (1991b).

Table 7-1 Major Meso-Cenozoic tectonic events in the northeastern Gulf of Mexico and the subjects discussed in Chapter Seven. The crustal types of the basement are adapted from Buffett (1989) and Salvador (1991b).

Table 8-1 Major Meso-Cenozoic tectonic events in the northeastern Gulf of Mexico and the subjects discussed in Chapter Eight. The crustal types of the basement are adapted from Buffett (1989) and Salvador (1991b).

Table 10-1 Major Meso-Cenozoic tectonic events in the northeastern Gulf of Mexico and the subjects discussed in Chapter Ten. The crustal types of the basement are adapted from Buffett (1989) and Salvador (1991b).
List of plates

Plate I. Line drawings of regional seismic profiles D1-D6 from the northeastern Gulf of Mexico.

Plate II. Line drawings of regional seismic profiles D7-D12 from the northeastern Gulf of Mexico.

Plate III. Line drawings of regional seismic profiles D13-D18 from the northeastern Gulf of Mexico.

Plate IV. Line drawings of regional seismic profiles D19-D24 from the northeastern Gulf of Mexico.

Plate V. Line drawings of regional seismic profiles D25-D30 from the northeastern Gulf of Mexico.

Plate VI. Line drawings of regional seismic profiles D31-D35 from the northeastern Gulf of Mexico.

Plate VII. Line drawings of regional seismic profiles S1-S5 from the northeastern Gulf of Mexico.

Plate VIII. Line drawings of regional seismic profiles S6-S8 from the northeastern Gulf of Mexico.

Plate IX. Regional sequence stratigraphic correlation chart from the northeastern Gulf of Mexico.

Plate X. A line drawing of an interpreted regional seismic profile from near mid-Cretaceous shelf to Perdido Fold Belt of the northwestern Gulf of Mexico, offshore Texas, USA.

Plate XI. Five line drawings of regional seismic profiles DL1-DL4 and SL1 from continental slope of the Niger Delta, Gulf of Guinea, offshore Nigeria.
List of maps

Map 1. Bathymetry Map

Map 2. Structure Map: Base of Salt (158.5 Ma) and Salt-free Basement (\( ? \) Ma)

Map 3A. Isopach Map: Upper Jurassic-Middle Cretaceous (150.5-91.5 Ma)

Map 3B. Estimated relative distribution of salt during mid-Cretaceous (91.5 Ma)

Map 4. Isopach Map: Middle Cretaceous-Present (91.5-0 Ma)

Map 5. Time-Thickness Map: Middle Jurassic-Lower Cretaceous (158.5-98 Ma)

Map 6. Time-Thickness Map: Allochthonous Salt

Map 7. Time-Structure Map: Top of Allochthonous Salt

Map 8. Time-Thickness Map: Supra-Allochthonous Salt Sediment

Map 9. Time-Thickness Map: Middle Cretaceous-Middle Oligocene (91.5-30 Ma)

Map 10. Time-Structure Map: Middle Oligocene (30 Ma)

Map 11. Time-Thickness Map: Middle Oligocene-Lower Miocene (30-15.5 Ma)

Map 12. Time-Thickness Map: Middle Miocene (15.5-10.5 Ma)

Map 13. Time-Thickness Map: Upper Miocene (10.5-5.5 Ma)

Map 14. Time-Thickness Map: Pliocene (5.5-1.9 Ma)

Map 15. Time-Thickness Map: Pleistocene-Present (1.9-0 Ma)

Map 16. Faults on Mid-Oligocene (30 Ma)

Map 17. Faults on Upper Miocene (5.5 Ma)

Map 18. Faults on Pliocene (1.9 Ma)
Chapter One

Introduction

1.1. Review

Widely distributed middle Jurassic salt (Louann and time equivalent) was the most important factor that controlled both structural styles and sediment accumulation patterns of the Gulf of Mexico basin and its onshore basins (e.g. East Texas Basin, North Louisiana Basin, Mississippi Salt Basin, Salvador, 1991a) during the Meso-Cenozoic. In the last decade, a great deal of effort was made to document (e.g. Wu et al, 1990b; MacGrae, 1990; Lee, 1990; Seni, 1991; DeBalko, 1991; Liro, 1992) and to understand the role of salt in the evolution of the Gulf of Mexico (e.g. Worrall and Snelson, 1989; Nelson, 1990; Ewing, 1991). New concepts on the behavior of salt and consequent structural and sedimentary signatures have been developed using deep seismic data (Worrall and Snelson, 1989; West, 1989; Wu et al, 1990b; Weimer and Buffler, 1992; Liro, 1992), and sophisticated modeling experiments (Jackson et al, 1988; Vendeville and Jackson, 1992a, 1992b; Talbot, 1992). Many studies concerning the origin of the Gulf of Mexico have been published (e.g. Buffler and Sawyer, 1985; Salvador, 1987; Buffler, 1989; Dobson and Buffler, 1991; Sawyer et al, 1991). The stratigraphy of the area was summarized by Shaub et al (1984), Winker and Buffler (1988), Weimer (1989), Wu et al (1990), Feng and Buffler (1991), Bartek et al, 1991 and Wornardt and Vail (1991). Various aspects of salt tectonics were reviewed by Jackson et al (1988), Worrall and Snelson (1989), Jackson and Cramez (1989), Wu et al (1989), West (1989), Nelson (1989), Wu et al (1990), Moretti et al (1990), Lowrie et al (1991), Liro (1992), Seni (1992) and Talbot (1992), and others. Salt and shale related extensional systems were discussed by many workers (e.g. Worrall

1.2. Objectives

This study concentrates on the timing of regional tectonic events, the structural styles and behavior of salt, extensional systems and contractual systems, the relationship between salt movements, extension and contraction, and the interaction of salt with sedimentation in the northeastern Gulf of Mexico. Using many deep reflection seismic profiles available from the oil industry, wells, biostratigraphy, regional sequence stratigraphy, extensive mapping, and structural analysis, I propose a model that describes the evolution of various salt structures and its control on the development of extensional systems involving various decoupling systems, regional contractual systems, and the formation of regional and local sedimentary basins.

1.3. Seismic and well data

The study area is shown in Figure 1-1. The area was selected to understand salt tectonics and its relationship with sedimentation, extension and compression. Geologically, this area is characterized by autochthonous, as well as obvious allochthonous salt
Figure 1-1 Location of the study area in the northeastern Gulf of Mexico and the regional Texas Transect. The study area covers the Mississippi and Alabama Shelf, the De Soto Canyon and Slope, part of the West Florida Terrace, Mississippi Canyon, the upper Mississippi Fan and the Louisiana Slope. The Texas Transect (in collaboration with D. Hall, B. Bowen, R. Rosen at TGS-CALIBRE Geophysical Company) extends from the mid-Cretaceous shelf margin onshore Texas to the Perdido Fold Belt. The physiography and bathymetry are from Bryant and Bryant (1991).
Figure 1-2. Seismic data and well information used in this study. Grid I, II and III are seismic data provided courtesy of TOTAL. Grid IV is mostly provided courtesy of GECO-PRAKLA and partly courtesy of TOTAL. All the well information is provided by TOTAL. Paleontological information, electric and/or sonic logs, check shot velocities and/or synthetic seismograms are available for wells 0-24. Electric and sonic logs, check shot and/or synthetic seismograms are available for wells 25-29. There are no stratigraphic information available for wells 25-29. The wells are 0-Sun #1, Destin Dome 166; 1- Mobil #1, Mississippi Sound 72; 2 - Chevron #1, Viosca Knoll 30; 3 - Shell #1, Main Pass 154; 4 - Shell #1, Main Pass 253; 5 - Chevron #2, Main Pass 264; 6 - Exxon #1, Mississippi Canyon 67; 7 - Amerada #1, Main Pass 177; 8 - Shell #1, Main Pass 183; 9 - Gulf #1, Main Pass 235; 10 - Shell #1, Main Pass 212; 11 - ARCO #1, Main Pass 229; 12 - AMOCO #1, Main Pass 280; 13 - American Petrofina #4, Mississippi Canyon 68; 14 - Placid #1, Mississippi Canyon 112; 15 - CONOCO #1, Mississippi Canyon 370; 16 - Humble #A-1, West Delta 12; 17 - Gulf #1, West Delta 35; 18 - California #1, West Delta 64; 19 - Pan Am #10, West Delta 75; 20 - Chevron #1, West Delta 109; 21 - Marathon #1, Mississippi Canyon 366; 22 - UNOCAL #1, Mississippi Canyon 455; 23 - Placid #1, Mississippi Canyon 839; 24 - Transco #1, Green Canyon 75; 25 - Shell #1, Mississippi Canyon 763; 26 - Shell #1, Mississippi Canyon 730; 27 - Shell #1, Mississippi Canyon 731; 28 - Shell #1, Mississippi Canyon 657; and 29 - Shell #1, Atwater Valley 471.
structures, growth fault systems with various decoupling levels, and a well-developed fold belt system (Mississippi Fan Fold Belt).

Figure 1-2 shows 2-D regional seismic data grids I-IV (courtesy of GECOPRAKLA and TOTAL) that cover most of the continental shelf offshore Mississippi, offshore Alabama, and a large part of the continental slope offshore Louisiana. The Texas Transect is based on TGS onshore and offshore lines (courtesy of TGS-Calibre) and the GBRS-1 line of TGS and Rice University.

Parts of seismic grids I and IV and wells 0-6 were used in a previous study (Wu, 1989) to calibrate the stratigraphy, to establish a sequence stratigraphic framework, and to understand the evolution of the allochthonous salt in the northeastern Gulf of Mexico. As a continuation of that project, grids I-IV are now integrated with 22 additional wells (wells 7-29) that document the geology of the study area. Grid I is composed of 2,400 mi of seismic data recorded to 8 seconds. This grid provides seismic images below the mid-Jurassic mother salt and is used to map the base of the autochthonous salt and the peripheral fault system. Grids II and III, recorded to 6-7 seconds, are used mostly for calibration and correlation of the stratigraphy. Grid IV is the main seismic data set that illustrates salt and slope tectonics offshore Louisiana. This data set provides excellent images down to 13 seconds and allows us to see seismic data below the mid-Jurassic mother salt.

1.4. Overview

A simplified map in Figure 1-3 shows the main structures of the study area. The distribution of mid-Jurassic salt controls the Meso-Cenozoic tectonic styles and sediment accumulation patterns in the Gulf of Mexico. Mid-Jurassic salt pinches out basinward of the Mississippi Fan Fold Belt and on parts of the west Florida shelf. The Meso-Cenozoic
Figure 1-3. Regional structural elements. Structural features are explained in the legend. Note that most of the mid-Jurassic salt is allochthonous and was emplaced in mid-Miocene-Pleistocene slope sediments. One significant autochthonous structure is the Destin Dome. The outline of the Destin Dome is from MacGrae (1990). Also note that the Mississippi Fan Fold Belt is located near the basinward limit of the mid-Jurassic salt basin.
Figure 1-4. Location of regional profiles in Chapter One. Figure 1-5 is about 600 km long and Figure 1-6 is about 220 km long.
sediments overlie the basement and show no structural deformation. In contrast, in the area underlain by mid-Jurassic salt, different kinds of structures occur. Related to the updip limit of the Jurassic salt basin, a peripheral fault system develops (e.g. Mexia, Talco, Pickens, Gilbertown fault zones, Ewing and Lopez, 1991). Salt rollers are common on the upper Jurassic and Lower Cretaceous slope and shelf areas (e.g. Bally, 1981; Wu et al, 1990b). Various autochthonous salt structures are observed in the eastern part of the basin. However, allochthonous salt structures of various stages dominate the continental slope. Complex extensional systems sole out on several decoupling zones. The short-lived Mississippi Fan Fold Belt marks the basinward limit of the mid-Jurassic salt basin. These complex structural systems intermingled and interacted with each other and with episodic sediment influxes throughout the Mezo-Cenozoic of the northeastern Gulf of Mexico.

A NE - SW section across the entire study area is shown in Figure 1-5 (see Table 1-1 for velocities used in depth conversion). It illustrates the base of salt, the west Florida shelf, the continental slope and structures, such as peripheral faults, autochthonous salt structures, pseudo-clinoforms, a primary weld on the base of mother salt, allochthonous salt structures of various stages, tertiary welds on allochthonous salt, primary, secondary and tertiary withdrawal basins, normal faults decoupled at various levels, and deformed sea floors over allochthonous salt structures. A NW - SE section in Figure 1-6 also shows typical structural styles on the continental slope. Figures 1-5 and 1-6 introduce some of the modern terminology used for salt tectonics, and the reader is also referred to the glossary in Appendix I of this thesis. Many intriguing and stimulating phenomena drive me to better understand the structural evolution of the region since mid-Jurassic time.

An overview of the structural styles on the continental slope can be obtained by referring to the regional cross sections D1-D35 and S1-S9 (Plates I-VIII) and Maps 1-18. Based on the salt distribution and structural styles, I subdivide the study area into several provinces as shown in Figure 1-7 for the convenience of discussion. The regional profiles
Note: Figures 1-5a and 1-5b are included in the pocket together with the plates and maps.
Note: Figures 1-6a and 1-6b are included in the pocket together with the plates and maps.
<table>
<thead>
<tr>
<th>TIME (Ma)</th>
<th>VELOC (m/s)</th>
<th>SLOPE AREA</th>
<th>FLORIDA ERRACE</th>
<th>BASE OF SALT MAP</th>
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</thead>
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<tr>
<td>S.EA WATER 0</td>
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<td>1,600-2,000</td>
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<tr>
<td>1.9</td>
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<td></td>
</tr>
<tr>
<td>5.5</td>
<td>L. MIocene</td>
<td>2,500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.5</td>
<td>M. MIocene 3</td>
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<td>2,500</td>
<td>2,500</td>
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</tr>
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<td></td>
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</tr>
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</tr>
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<td>4,500</td>
</tr>
</tbody>
</table>

Table 1-1 Interval velocities for depth conversion. This table is compiled using well data.
Figure 1-7a. Province map of the study area. See Figure 1-7b for geographic area names.

**WFT**- West Florida Terrace area: This is an area with very thin or no primary salt. It was a tectonically quiet area during most of the Meso-Cenozoic time.

**MAD**- Offshore Mississippi and Alabama and Destin Dome area: This area has relative thin salt and thick Mesozoic sediments. Except for Destin Dome, most of the tectonic activity occurred before mid-Cretaceous.

**VDL**- Viosca Knoll, part of De Soto Canyon and Lloyd Ridge areas: Most of the salt was displaced basinward under thick pre-mid-Cretaceous slope sediments. Minor allochthonous salt bodies were emplaced during mid-Cretaceous. Normal faults developed as salt withdrew. The primary weld, pseudo-clinoforms and turtle structures are typical.

**EMC**- East of Mississippi Canyon area: This area is characterized by isolated primary allochthonous salt tongues and sheets. Primary withdrawal basins are common. Tectonically active since Neogene. Primary, secondary and tertiary exist.

**WMC**- West of Mississippi Canyon and part of Atwater areas: This area is characterized by large coalesced and relatively undeformed primary allochthonous salt sheets. Turtle structures and primary withdrawal basins and related normal faults are common. GCWR- Green Canyon and part of the Walker Ridge areas: Various generations of allochthonous salt and welds are typical. Various supra-allochthonous basins and structures exist. Deformed primary and secondary allochthonous salt created sea-floor highs (e.g. Sigsbee Escarpment).

**MFFB**- Mississippi Fan Fold Belt: The fold belt formed during mid-Miocene along the basinward limit of mid-Jurassic Louann salt and basinward to the large allochthonous salt provinces. The fold belt involves only minor amounts of lateral shortening (less than 2 km). Some allochthonous salt and diapirs formed from the salt core of the foldbelt.

**AV**- Southern Atwater Valley and Lund areas: This area has no salt deposition and remains structurally stable since early Cretaceous.
Figure 1-7b. Offshore areas in the northeastern Gulf of Mexico.
and the maps show that this area had a very complicated geologic history, primarily due to the deformation of mid-Jurassic salt. Table 1-2 summarizes the key tectonic events for each of the provinces. These tectonic events are documented and illustrated in the following chapters.

<table>
<thead>
<tr>
<th>Time Interval</th>
<th>AV</th>
<th>MFFB</th>
<th>GCWR</th>
<th>WMC</th>
<th>EMC</th>
<th>VDL</th>
<th>MAD</th>
<th>WFT</th>
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<td>18.5</td>
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Table 1-2 Major Meso-Cenozoic tectonic events in the northeastern Gulf of Mexico. The crustal types of the basement are adapted from Buffler (1989) and Salvador (1991b).
1.5. Approach

As a continuation of previous work (Wu, 1989; Wu et al, 1990b), I tackled the problem with a careful regional stratigraphic correlation using all available information. This correlation allows me to date structural and sedimentary events since mid-Jurassic time. A detailed regional sequence stratigraphic framework was established. Based on this framework, a suite of cross sections (Plates I-VIII), isopach maps, time-thickness maps and structure maps (Maps 1-18) document the geology of the northeastern Gulf of Mexico. Various structural styles are illustrated. A regional cross-section from the northwestern Gulf of Mexico is compared with the profiles from the northeastern Gulf of Mexico. Efforts were also made to compare Gulf Coast salt tectonics with shale tectonics as observed on selected seismic profiles from offshore Nigeria. Finally, a geological model integrating salt tectonics, extension, compression and sedimentation is proposed for the northeastern Gulf of Mexico. Conceptual models are also proposed for the development of the structural styles of the northwestern Gulf of Mexico and Offshore Nigeria.
Chapter Two

Sequence Stratigraphy

Sequence stratigraphic concepts (e.g. Vail, 1977) were applied to establish the stratigraphic framework of the area. Plate IX (modified from Wu et al, 1990a) shows the sequence stratigraphic chart used in this study. Biostratigraphic information (mostly benthic tops), electric well logs, check shot velocities, synthetic seismograms at the wells and regional reflection seismic programs are integrated. I used my sequence stratigraphic framework to date the various stages of salt movement, extension and the formation of the Mississippi Fan Fold Belt.

2.1. Sequence stratigraphic interpretation of well information

Twenty-five wells (wells 0-24) with biostratigraphic information are interpreted and correlated with seismic data as shown in Figures 2-1 and 2-2. The sequence stratigraphic correlation obtained from the previous study (Wu, 1989) is used to date the Mesozoic sequences of the slope area. Two examples of the regional correlation offshore Mississippi and Alabama are shown in Figure 2-3. In the previous study, stratigraphy was controlled by well information down to the top of mid-Jurassic Louann salt as shown in well-log Transect I Figure 2-4. Although I have very good stratigraphic control over the mid-Cretaceous shelf, the complexity of structures in the slope area requires relatively more closely spaced well control. I chose wells (wells 7-24) that have deep penetration, biostratigraphic information, check shot velocities and, preferably, synthetic seismograms as my key stratigraphic control. Well logs without paleontologic information from some
Figure 2-1. Index map for seismic examples and regional line drawings of seismic profiles of Chapter Two.
Figure 2-2. Location of well control and well-log transects. The wells are 0-Sun #1, Destin Dome 166; 1-Mobil #1, Mississippi Sound 72; 2-Chevron #1, Viosca Knoll 30; 3-Shell #1, Main Pass 154; 4-Shell #1, Main Pass 253; 5-Chevron #2, Main Pass 264; 6-Exxon #1, Mississippi Canyon 67; 7-Amerada #1, Main Pass 177; 8-Shell #1, Main Pass 183; 9-Gulf #1, Main Pass 235; 10-Shell #1, Main Pass 212; 11-ARCO #1, Main Pass 229; 12-AMOCO #1, Main Pass 280; 13-American Petrofina #4, Mississippi Canyon 68; 14-Placid #1, Mississippi Canyon 112; 15-COCA #1, Mississippi Canyon 370; 16-Humble #A-1, West Delta 12; 17-Gulf #1, West Delta 35; 18-California #1, West Delta 64; 19-Pan Am #10, West Delta 75; 20-Chevron #1, West Delta 109; 21-Marathon #1, Mississippi Canyon 366; 22-UNOCAL #1, Mississippi Canyon 455; 23-Placid #1, Mississippi Canyon 839; 24-Transco #1, Green Canyon 75; 25-Shell #1, Mississippi Canyon 763; 26-Shell #1, Mississippi Canyon 730; 27-Shell #1, Mississippi Canyon 731; 28-Shell #1, Mississippi Canyon 657; and 29-Shell #1, Atwater Valley 471.
Note: Figure 2-3 is included in the pocket together with the plates and maps.
Note: Figure 2-4 is included in the pocket together with the plates and maps.
Note: Figure 2-5 is included in the pocket together with the plates and maps.
recent deep-water wells (25-29) were used to help understand the lithologic changes through time in the deep Gulf of Mexico.

One additional regional well-log section, Transect II (Figure 2-5), was constructed to show the changes of stratigraphy from shelf to slope. The summary of key stratigraphic control from wells, generalized lithology of the northeastern Gulf of Mexico and their relationship with eustatic sea-level changes and relative coastal onlaps are illustrated in Figure 2-6. From the shelf to the slope, the penetrations of wells become younger in geologic time. Thus, seismic correlation based on the stratigraphic framework on the shelf area and the deep wells in the slope are critical to establish my stratigraphic framework in the slope area.

2.2. Sequence stratigraphic correlation of regional seismic profiles

The sequence boundaries and key flooding surfaces obtained from well information are tied to the regional seismic database using available check shot velocities and synthetic seismograms. Figure 2-3 (after Wu et al, 1990a) shows two regional profiles from offshore Mississippi and Alabama where deep stratigraphic control is available. The key sequence boundaries and flooding surfaces in Figure 2-3 are correlated in the slope area using seismic data. Additional well information (wells 7-24) in the slope area is also correlated to the seismic data. Figures 2-7, 2-8 and 2-9 show three examples of well control on seismic profiles. These wells were critical for the correlation of Tertiary-Present stratigraphy throughout the slope area. Other wells summarized in Figure 2-6 are also tied to seismic profiles and control the stratigraphic correlation.

The major sequence boundaries shown on Plate IX are correlated on well-logs (e.g. Figures 2-4 and 2-5) and seismic sections. Each of the correlated surfaces are loop-tied on closely spaced seismic profiles (2x4 mi and 2x2 mi in grid IV from GECO-
Figure 2-6. Main sequence stratigraphic surfaces, well control, lithology, relative changes of coastal onlaps, and long term Eustatic sea level changes. See Figure 2-2 for well locations. The vertical scale is arbitrary. Note the condensed interval between 91.5 Ma and 30 Ma. Long-term Eustacy and relative coastal onlaps are from Haq et al (1987). Plio-Pleistocene sequence boundaries are modified according to Wornardt and Vail (1991). Lithology is adapted from Salvador and Muñeton (1991).
Figure 2-7a. An uninterpreted well-tie seismic section. See Figure 2-1 for location of seismic line.
Figure 2-7b. An interpreted well-tie seismic section. See Figure 2-1 for location of seismic line and Figure 2-2 for well location. A primary weld formed when mother salt was evacuated. Deformed pre-mid-Cretaceous strata show partially developed pseudo-clinoforms. Mid-Cretaceous allochthonous salt was emplaced below MCFS (91.5 Ma) surface. The mid-Cretaceous allochthonous salt was reactivated since Late Miocene under increased Neogene sediment load as shown by the overlying normal faults. See Plate IX for the age of correlated surfaces.
Note: Figure 2-8a is included in the pocket together with the plates and maps.
Note: Figure 2-8b is included in the pocket together with the plates and maps.
Figure 2-9a. An uninterpreted well-tie seismic section with a turtle structure. See Figure 2-1 for location of seismic line.
Figure 2-9b. An interpreted well-tie seismic section of Figure 2-9a. See Figure 2-1 for location of seismic line and Figure 2-2 for well location. A primary weld, tension faults over the turtle structure and a part of the allochthonous salt are shown. See Plate IX for the age of the correlated surfaces.
PRAKLA and TOTAL). Key well control locations and the closely spaced seismic grid allowed the correlated surfaces to be tied. Only a few cases of "jump correlation" occurred in the presence of shallow allochthonous salt. There is no stratigraphic information from wells in the lower slope (southern end of the study area, e.g. wells 25-29). These wells are tied with seismic data to obtain some knowledge of lithologic changes in the middle and lower slope area. The correlation of the lower slope province is achieved using remote well information on the shelf and upper slope (wells 0-29) and closely spaced seismic data.

Base of salt (Plate IX; or basement where there is no salt) is carried across the area where it can be reasonably interpreted and tied to the seismic. This correlation is based on the previous study (e.g. Figure 2-3; Wu, 1989) and on seismic character. In the Jurassic salt province, most of the salt and its overburden have been deformed. Below the basement, there are usually no reflections. In the eastern end of the study area, the base of salt is often a strong reflector. This surface is correlated throughout most of the eastern and southern portions of grid IV (Figure 1-2) where the basement can be recognized. Closely spaced seismic profiles made the correlation of this surface reasonable on a regional scale (see Map 2). Over most of the northwestern slope area where there are shallow allochthonous salt structures, seismic imaging is difficult (due to energy penetration problems through allochthonous salt, complex overlying structures, strong lateral velocity variation due to shallow salt and time migration, etc.) and, thus, the basement reflector is very poorly defined.

The Middle Cretaceous Flooding Surface (91.5 Ma, MCFS in short, see Wu et al, 1990a) and its deep-water equivalent are correlated regionally. This surface appears on seismic profiles as a very low frequency and high amplitude reflector below which angular unconformities are often observed. This seismic marker can be correlated throughout most of the slope where there is no allochthonous salt. This surface corresponds to the end of Lower Cretaceous deep-water off-reef deposits. This also marks the beginning of an
extended period of condensed sedimentation related to the peak sea-level rise at 91.5 Ma (Figure 2-6; Haq, 1987) and the corresponding lack of sediment supply (Winker, 1982) in the basinal area.

Immediately above the MCFS (91.5 Ma), the mid-Oligocene (30 Ma) sequence boundary is correlated as extensively as the MCFS (91.5 Ma) surface. The MCFS-mid-Oligocene (91.5-30 Ma) interval is easily recognized on seismic profiles as a band of high amplitude, low frequency and continuous reflectors. The interval between 91.5-30 Ma represents the longest sediment starvation period in the northeastern Gulf of Mexico (Figure 2-6, Wu et al, 1990a). The mid-Oligocene sequence boundary (30 Ma) marks the end of sediment starvation. Chaotic zones representing fast sedimentation are often observed overlying this surface. Since mid-Oligocene (30 Ma), sedimentation increased rapidly.

Important Miocene sequence boundaries of 15.5 Ma, 13.8 Ma, 10.5 Ma and 5.5 Ma are also correlated over the whole area. These sequence boundaries control the interpretation of the Cenozoic tectonic history of the northeastern Gulf of Mexico. With increased sediment influx since mid-Oligocene (30 Ma), especially during the Miocene, pre-existing salt structures were revitalized and further developed. The Miocene is the most important tectonic development period in the history of the northeastern Gulf of Mexico. During the Miocene, allochthonous salt tongues, the Mississippi Fan Fold Belt and extensive extensional systems were formed.

Finally, the late Pliocene sequence boundary 1.9 Ma is correlated across the entire slope area. This surface is very characteristic on seismic data and often associated with an overlying chaotic fan complex. This surface is important for understanding the post-emplacement history of the allochthonous salt and related fault systems.
2.3. Sequence stratigraphic framework

As a result of the regional stratigraphic correlation, a sequence stratigraphic correlation chart Plate IX and Figure 2-6 was constructed to form the basis of this structural study. Plate IX (after Wu et al, 1990a) has been updated to include the 2.6 Ma sequence boundary according to Wornardt and Vail (1991). The 1.6 Ma sequence boundary is changed to 1.9 Ma following Wornardt and Vail (1991). Two additional middle Miocene sequences (13.8 and 12.5 Ma) are correlated giving more detailed timing of Miocene structural events.

Overlying the widely distributed mid-Jurassic (Callovian, Salvador, 1991a) Louann salt are the eolean and marine Norphlet sands which occur near the updip limit of Louann salt (Tew, et al, 1991; Salvador, 1991a). On top of Norphlet are the Smackover (150.5-144 Ma) carbonates (see Plate IX and Figure 2-6). In most onshore areas, they are about 200 meters thick (Salvador, 1991). Smackover and its time equivalent interval thickens toward the offshore Mississippi and Alabama area (e.g. Lines A and B in Figure 2-3) where it reaches 1,600 m. The interval pinches out or becomes very thin near the mid-Cretaceous platform margin (Figure 2-3) and cannot be differentiated in the slope area.

The Smackover is overlain by the thick siliciclastic Haynesville and Cotton valley (144-128.5 Ma, see Plate IX) section, which progrades over the previous platform margin. This interval reaches about 3,000 meters near the Late Jurassic shelf margin (e.g. Figure 2-3). On top of the Cotton Valley are the Lower-middle Cretaceous platform carbonates (128.5-91.5 Ma; Plate IX; McFarlan and Menes, 1991) that ended with the 91.5 Ma (Haq, et al 1987; Plate IX) transgression. An extended period of condensed sedimentation followed Turonian transgression (91.5 Ma) until mid-Oligocene (30 Ma, Wu et al, 1990a). Sequences in this interval are recognizable in the offshore Mississippi and Alabama, Destin Dome and on the Florida Terrace areas (e.g. Figures 1-5 and 2-3) but become very condensed in the slope area (Figures 2-6, 2-7, 2-8 and 2-9). The sedimentation during
mid-Cretaceous - mid-Oligocene centered in the onshore areas and the western Gulf of Mexico (Winker, 1982; Sohl et al, 1991; Galloway et al, 1991; Salvador, 1991b). Since mid-Oligocene (30 Ma), sequences expanded (e.g. Figure 2-3) on deltaic depocenters in the slope area and shifted from the western Gulf of Mexico toward my study area (e.g. Winker, 1982; Galloway et al, 1991; Salvador, 1991b; Coleman et al, 1991). Key sequence boundaries, i.e. 15.5 Ma (LM, lower Miocene), 13.8 Ma (MM1, the early Middle Miocene), 12.5 Ma (MM2, the middle Middle Miocene), 10.5 Ma (MM3, the late Middle Miocene), 5.5 Ma (UM, Upper Miocene) and 1.9 ma (PLI, Pliocene) allow me to time the evolution of allochthonous salt, the Mississippi Fan Fold Belt, various extensional systems and local sedimentary basins.

2.4. Pattern of sediment distribution

The post-mid-Jurassic sediment distribution in the northern Gulf of Mexico varies from Mesozoic to Cenozoic. Generalized shifting Mesozo-Cenozoic depocenters are shown in Figure 2-10 (after Salvador, 1991a, 1991b; McFarlan and Menes, 1991; Sohl et al, 1991; Galloway et al, 1991). Pre-mid-Cretaceous sediments are widely distributed onshore and offshore in the northern Gulf of Mexico landward toward the mid-Cretaceous shelf margin (e.g. Salvador, 1991a, McFarlan and Menes, 1991). The Upper Cretaceous is thin over most parts of the Gulf, except for the western part of the Gulf (e.g. Sohl, et al, 1991). Instead, Cenozoic sedimentation has been very localized and has shifted from the western to the eastern Gulf of Mexico (e.g. Winker, 1982; Galloway, et al, 1991; Salvador, 1991b).

The sediment distribution in the study area is documented in detail with a series of isopachs and time-thickness maps (Maps 3, 4, 9, 11, 12, 13, 14 and 15) for the offshore Louisiana slope area. The sedimentation history can be subdivided into three periods.
Figure 2-10. Location of Late Jurassic-Cenozoic depocenters in the northwestern Gulf of Mexico (after Salvador, 1991a, 1991b; McFarlan and Menes, 1991; Sohl et al, 1991; Galloway et al, 1991). The pre-mid-Cretaceous sedimentation was concentrated landward of the mid-Cretaceous shelf margin. Upper Cretaceous is generally condensed over most of the northern Gulf of Mexico. Paleocene depocenters are located to the north of the mid-Cretaceous shelf margin. Eocene and Oligocene depocenters occur in the western part of the Gulf of Mexico. Since Early Miocene time depocenters began to shift to the east. Since Middle Miocene large amount of sediments deposited in the study area and triggered the massive diapirism of salt which consequently caused the shortening in the Mississippi Fan. As sediment loads increased since Middle Miocene, various allochthonous salt structures, welds, salt withdrawal basins, turtle structures and extensional growth faults developed.
A first period of sedimentation between the end of mid-Jurassic Louann salt deposition (150.5 Ma) and the mid-Cretaceous transgression affects the whole Gulf of Mexico Basin. The thickest depocenters are landward of the mid-Cretaceous shelf margin (Figure 1-3). Map 3A shows only the sediment distribution basinward of the mid-Cretaceous shelf margin. We can see that the interval thickens toward the shelf margin. Between the mid-Cretaceous shelf margin and the basinward limit of the mid-Jurassic salt basin, the thickness of this interval varies greatly. The thickness of the platform near the margin is about 7 km and reaches a stable 3 km over the salt-free lower slope. In the slope area the thickness varies from 5 km to less than 1 km. As will be discussed later, this thickness variation reflects early salt deformation. Regionally, the rate of sedimentation is about 120 m/Ma at the shelf margin and 50 m/Ma at the lower slope.

An extended period of starved sedimentation from the mid-Cretaceous transgression (91.5 Ma) to the mid-Oligocene (30 Ma) regression characterized the second sedimentary period. Map 9 shows the time-thickness map of the starved interval. Overall this interval is thin and mostly deposited landward and on the underlying mid-Cretaceous carbonate platform as shown Figure 2-3 (Line A) and Figure 1-5. The thickness changes from about 1.5 km in the salt-free lower slope to nearly zero toward the mid-Cretaceous shelf margin. This shows that the sediment in the lower slope may derive from the southwest. The rate of sedimentation ranges from near zero to about 25 m/Ma. As shown later this period of starvation coincides with the stabilization of the previously formed salt structures.

A third major period of sedimentation is dominated by the prograding clastic depocenters of the mid-Oligocene to present interval. Map 4 shows the total mid-Cretaceous (91.5 Ma) to present isopach. As the influence of the 91.5-30 Ma interval is negligible, Map 4 reflects mostly the mid-Oligocene to present sedimentation. In contrast with Map 3A, we can see that the post-Oligocene sediments fill the deep basin beyond the
mid-Cretaceous shelf margin. The rate of sedimentation ranges from 300 m/Ma at the present shelf margin to 230 m/Ma at the northwestern lower slope and about 100 m/Ma in the eastern part of the map area. The mid-Oligocene-Present interval within the salt province varies greatly, reflecting alternatively the presence of allochthonous salt, large local withdrawal basins and the Mississippi Fan Fold Belt.

The mid-Oligocene-Present sediments are highly involved with salt, extension and contraction tectonics. Several maps shows subdivisions of this time interval. Map 11 shows the mid-Oligocene to Lower Miocene interval (30 Ma-15 Ma). Overall, this interval thins to the south with some expansion in the north. As will be elaborated later, this expansion suggests the first reactivation of the mid-Cretaceous salt structures. Over the lower slope and the Mississippi Fan Fold Belt, the thickness remains relatively uniform. The Middle Miocene (15.5-10.5 MA) interval (Map 12) shows sediment thinning over the Mississippi Fan folds and thickening to the north and west. This suggests that the Mississippi Fan Fold Belt formed during this period corresponding to rapid overall thickness increases in the whole study area. During the Late Miocene (10.5-5.5 Ma) interval shown on Map 13, the sediments are mainly deposited landward of the Mississippi Fan Fold Belt and trapped within the primary withdrawal basins behind the basinward spreading allochthonous salt bodies. In contrast the area of large allochthonous salt has almost no Upper Miocene sediments. Over the Mississippi Fan Fold Belt and the salt-free area to the south, the Upper Miocene is very thin compared to the trapped coeval sediments to the north. The Upper Miocene thins from west to east. The distribution of Upper Miocene sediments is thus greatly influenced by the formation of allochthonous salt, the Mississippi Fan Fold Belt and the large primary withdrawal basins as discussed in the following chapters. The Pliocene (5.5-1.9 Ma) thickness (in time) of Map 14 shows again that thick sediments are accumulated behind and also above the allochthonous salt. In the supra-allochthonous-salt basins in the Green Canyon area, the thickness varies
Figure 2-11. This figure shows typical Meso-Cenozoic thicknesses, duration of correlated interval and rates of sedimentation on slope in the northeastern Gulf of Mexico. The intervals are P (0.19 Ma), PLI (1.9-5.5 Ma), UM (5.5-10.5 Ma), MM (10.5-15.5 Ma), LMMO (15.5-30 Ma), MOMC (30-91.5 Ma), MCTS (91.5-150.5 Ma). Note the rapid increase of sedimentation rate during Middle Miocene after a long period of slow sedimentation. Plio-Pleistocene sedimentation has the highest rate during the development of the Mississippi Delta.
greatly. Pliocene sediments in the fold belt area and the salt-free area thicken to the west. During the Pleistocene-Present interval (1.9-0 Ma) documented on Map 15, the sediments are mainly deposited over the allochthonous salt and the salt-free lower slope. A large amount of Mississippi Fan sediments accumulated over the lower slope basinward of the allochthonous salt.

For each of the mapped Meso-Cenozoic intervals, the duration of the interval, typical thickness and typical rates of sedimentation are summarized in Figure 2-11. The pre-mid-Cretaceous interval has the thickest sediments and a low rate of sedimentation. The condensed mid-Cretaceous-mid-Oligocene interval is the longest and has the lowest rate of sedimentation. After mid-Oligocene, the Middle Miocene shows the first rapid increase of sedimentation. Following the decreased rate of sedimentation during the Late Miocene, the Pliocene-Present sedimentation increased continuously in response to the development of the Mississippi Fan.

Sequence stratigraphy and sediment isopachs formed the basis for the understanding of regional tectonic and sedimentary history of the northeastern Gulf of Mexico.
Chapter Three

Configuration of the Basement and Distribution of Mid-Jurassic Salt

The basement configuration and the distribution of the mid-Jurassic salt controlled the Meso-Cenozoic tectonic provinces of the study area. Table 3-1 shows the context of the subjects to be discussed in this chapter.

Table 3-1 Major Meso-Cenozoic tectonic events in the northeastern Gulf of Mexico and the subjects discussed in Chapter Three. The crustal types of the basement are adapted from Buffler (1989) and Salvador (1991b).
The mid-Jurassic Luann salt covers most of the northern Gulf of Mexico as shown in Figure 3-1 (e.g. Martin, 1978; Salvador, 1987; Buffler, 1989). The updip zero edge of the salt is associated with the peripheral fault systems (e.g. Luling-Maxia-Talco-South Arkansas-Pickens-Gilbertown-Pollard fault zones; Martin, 1978; Ewing, 1991) of the onshore area. On the Florida Terrace the updip limit is near the eastern end of the Destin Dome area (see Figure 1-3 and Map 2). The southeast end of the Jurassic salt basin off of the Florida Escarpment is shown on Figures 3-2 and 3-3a. Basinward the salt basin pinches out at the southern margin of the Perdido Fold Belt to the west (Figure 3-3b, Buffler, 1989), and the Mississippi Fan Fold Belt to the east. In the central part of the Gulf of Mexico basin the basinward edge of the salt basin is obscured by shallow allochthonous salt. The relative thickness of salt deposited varies in the basin as shown in Figure 3-2 (Salvador, 1987). Salt is thinner on the edge and thick in the center of the basin. According to Salvador (1991), the original salt is estimated to be as thick as 2-3 km in the Texas-Louisiana continental slope. Although the exact thickness of the original salt is hard to estimate, the amount of salt deposited has to be large just by looking at the amount of salt we see today (e.g. Map 6 showing the time-thickness of the allochthonous salt in the study area). The distribution of salt reflects the mid-Jurassic basin configuration (Salvador, 1987; Buffler, 1989; Dobson and Buffler, 1991; Salvador, 1991a). Different opinions exist about the early basin evolution (Pindell, 1985; Buffler and Sawyer, 1985; Hall et al, 1982; Klitgord et al, 1984), the type of crust on which salt was deposited, the structure of the basement (Hall et al, 1982; Buffler and Sawyer, 1985; Salvador, 1991), and the features related to the opening of the Gulf of Mexico.

In the northeastern Gulf of Mexico basin the geometry and type of crust of the mid-Jurassic salt are relatively well documented by seismic data, gravity and magnetic data (e.g. Buffler, 1989; Buffler and Sawyer, 1985; Wu et al, 1990b; Dobson and Buffler, 1991; Salvador, 1991; Hall, 1992; and proprietary magnetic and gravity data). Crustal
Figure 3-1. Distribution of salt structures and regional tectonic features in the Gulf of Mexico (from Martin, 1978). Note the peripheral fault systems (e.g. Mexia, Talco, Pickens, Giber Town and Pullard fault zones) near the updip limit of mid-Jurassic salt landward to the mid-Cretaceous shelf margin. Also note the extensive normal faults basinward to the mid-Cretaceous shelf margin and the extensive salt structure on Texas and Louisiana slope. (1) Reverse faults; (2) Peripheral fault system; (3) Normal growth faults; (4) Regional anticline or arch; (5) Salt diapirs or massifs and salt anticlines and swells; (6) Shale domes and anticlines; (7) Mid-Cretaceous shelf margin; (8) Updip limits of Louann salt; (9) Uplifts of exposed Paleozoic strata and crystalline basement rocks; (10) Inner margin of Cretaceous and Tertiary coastal plain deposit; (11) Downdip limits of deep wells reaching rocks of Ouachita tectonic belt.
Figure 3-2. Distribution and relative thickness of Mid-Jurassic Louann salt in the Gulf of Mexico (from Salvador, 1987).
Figure 3-3a. Salt distribution and its relationship to the oceanic crust (from Salvador, 1991b). Note that part of the oceanic crust is overlain by mid-Jurassic salt.
Figure 3-3b. Basement configuration and its relationship with salt of the Gulf of Mexico (from Buffler, 1989). Salt is underlain by transitional crust. The Mississippi Fan Fold Belt and Perdido Fold Belt are located at the basinward limit of the mid-Jurassic salt.
types, salt distribution and important structural elements for the Gulf of Mexico are shown in Figure 3.3a (Buffler, 1989). Hall et al (1982), Buffler and Sawyer (1985), Buffler (1989), Dobson and Buffler (1991), Sawyer et al (1991), and Salvador (1991) all suggest that the deep-water salt-free province is underlain by oceanic crust. The oceanic crust may also (e.g. Hall et al, 1982; Salvador, 1991b, Figure 3-3a; Hall et al, 1992) or may not be partly underlying the salt province (e.g. Buffler, 1989, Figure 3-3b). Figure 3-3b (Salvador, 1991b) shows that the oceanic crust is partly underneath the Jurassic salt basin. This is in agreement with my inspection of proprietary gravity and magnetic data compiled by BP. However, much of the salt province is underlain by thin and thick transitional crust (Figure 3-3b; e.g. Buffler and Sawyer, 1985; Buffler, 1989). The updip salt-free area is underlain by continental crust (Figure 3-3b). Since the objective of this project is to understand the post-salt tectonics and sedimentation, the exact nature of the crust and its boundaries is not our immediate concern. The differences of the crustal types underneath the mid-Jurassic salt basin do not prevent us from understanding the post-salt tectonics of the northeastern Gulf of Mexico. On the other hand, the distribution of the mid-Jurassic salt is critical for the location and development of the Miocene Mississippi Fan Fold Belt.

Map 2 shows the structure of the base of salt and the top of salt-free basement as well as the distribution of mid-Jurassic allochthonous salt over the study area. The distribution of salt generally follows the depth contours in the Destin Dome and De Soto Canyon areas. The peripheral fault systems to the east (Map 2, Figures 2-3 and 1-5; MacGrae, 1990) clearly mark the updip limit of the mid-Jurassic salt basin. As illustrated in Figure 1-5, the peripheral faults bound the eastern end of the salt basin. Figure 3-5 is a NE - SW seismic cross section that shows the basinward transition from the salt province to a salt-free province. The section above salt is clearly deformed while the section above the salt-free province is undeformed. In the central and western parts of my study area, the basinward edge of the salt basin coincides with the southern limit of the Mississippi Fan
Figure 3-4. Index map for seismic examples in Chapter Three.
Note: Figure 3-5a is included in the pocket together with the plates and maps.
Note: Figure 3-5b is included in the pocket together with the plates and maps.
Fold Belt. As shown on Map 2, the Mississippi Fold Belt coincides with the basinward limit of the mid-Jurassic salt province. Beyond the fold belt there is no indication of any typical salt-related features. Thus the salt-free province shown on Figures 3-5 and 1-6 is characterized by an undeformed flat section overlying the reflection-free basement.

In addition to the distribution of salt, in the northeastern Gulf of Mexico, Map 2 shows the depth contours of the base of the mid-Jurassic salt basin and the basement contours of the salt-free area. The base of salt is generally a gently warped basinward dipping monocline with an overall dip of about 2 degrees. The exception is near the Florida Escarpment where the dip of basement reaches about 8 degrees as calculated from Map 2. This basement flexure coincides and is probably mostly due to Tertiary sediment loading. The shallowest base of salt is about 7 km in the Destin Dome area. The deepest basement reaches 13 km in the northwest Mississippi Canyon area, the west Atwater Valley and the southeast Green Canyon areas. In the same area, we can see the peripheral fault system that marks the updip limit of the salt basin. In most of the Destin Dome area, the base of salt shows a relative depression where some autochthonous salt structures are observed such as Destin Dome itself (Figure 1-5). To the south, over most of the De Soto Canyon area, a salt-free basement high is separated from the lower Destin Dome area and some of the De Soto Canyon area coincides with the overlying peripheral fault system as shown on Map 2 and published studies (e.g. McGrae, 1990). In the lower slope area, the relatively deep base of the salt gradually rises to a relatively higher salt-free basement as clearly shown by Figure 3-5 and Map 2. A flexure in the basement suggests that on this profile (with approximately four times vertical exaggeration) the salt appears to be deposited in a basement depression. This flexure is also shown on Map 2 (see Figure 3-4 to locate Figure 3-5 on Map 2). West of the flexure is a flat salt-free, probably oceanic, basement. Over most of the area, similar flexures are not seen for two reasons. First, the flexure of the basement along the southern salt basin edge is minor (Map 2 and regional
profiles D1-D20). Second, most of the other profiles are not displayed with the dramatic vertical exaggeration of Figure 3-5. The overlying salt pinches out onto the salt-free basement. Figure 3-5 shows us what the basinward limit of salt might have looked like in the Mississippi Fan Fold Belt area before the fold belt was formed during Middle-Late Miocene time. The geometric and mechanical boundary between the salt and the salt-free basement determines the location of the Mississippi Fan Fold Belt. The importance of the basinward salt limit for the development of the Mississippi Fan Fold Belt will be elaborated in Chapter Seven. Aside from the edge of the salt, the base of salt is generally a basinward dipping monocline. I have not seen any significant faults on or below that surface. Only a few minor normal faults are observed in the southeast corner of the study area as shown on Map 2 and profiles S7-S9. I also have not seen any positive evidence of a strike slip or transfer fault that cuts across the base of salt along the portion of the Florida Escarpment in my study area.

The Meso-Cenozoic complex of sedimentary and tectonic systems developed over the described salt province. I will document and analyze each of the major sedimentary and tectonic events and finally explain their inter-relationship in the following chapters.
Chapter Four

Pre-Mid-Cretaceous Sedimentation and Salt Movements

The first period of deformation of the Louann salt began soon after its deposition (150.5 Ma) and lasted until the mid-Cretaceous (Turonian, 91.5 Ma) transgression. During this period of time (150.5-91.5 Ma), sedimentation was continuous and the sediments were dominantly carbonates (e.g. Cook and Bally, 1975; Winker and Buffler, 1988; Salvador, 1991a; McFarlan and Menes, 1991). By the end of Lower-Cretaceous, widespread carbonate platforms developed around the Gulf of Mexico (e.g. Figure 4-2; Cook and Bally, 1975; McFarlan and Menes, 1991). Time equivalent deep-water deposits accumulated on the slope (Map 3A). In response to the sediment loads over the salt, various stages of initial salt deformation occurred in my area. As a result salt structures formed below the carbonate platforms and within the off-reef deep-water basin. The tectonic context and events discussed in this chapter are shown in Table 4-1.

4.1. Pre-mid-Cretaceous deformation on the shelf

Following the deposition of mid-Jurassic salt (Callovian, e.g. Salvador, 1987; Salvador, 1991a), mostly eolian and marine Norphlet sands (Tew, et al, 1991; Salvador, 1991a) were deposited on top of the Louann salt. In the onshore northeastern Gulf basin, Norphlet sands are distributed near the updip limit of the Louann salt (e.g. Tew, et al 1991; Salvador, 1991a). It is not known whether the Norphlet thins or pinches out basinward in the area under the mid-Cretaceous shelf margin. Since the distribution and thickness of Norphlet can only be observed near the updip limit of the salt, the known deformation of salt resulting from Norphlet loading is limited to the vicinity of the updip limit of salt.
Table 4-1 Major Meso-Cenozoic tectonic events in the northeastern Gulf of Mexico and the subjects discussed in Chapter Four. The crustal types of the basement are adapted from Buffler (1989) and Salvador (1991b).
Figure 4-1. Index map for seismic examples of Chapter Four.
Figure 4-2a. Lithofacies-paleogeographic map, Albian (from Sohl et al., 1991). Note the widespread carbonate platform all around the Gulf of Mexico.
Figure 4-2b. Lithofacies-paleogeographic map, middle Cenomanian through Turonian (from Sohl et al, 1991). Note the demise of the carbonate platform in the northern Gulf of Mexico after the Turonian transgression. See Plate IX for the relative changes of sea levels.
Following the Norphlet, the Smackover carbonate section was deposited (e.g. Plate IX and Figure 2-3; Cook and Bally, 1975; Salvador, 1991a). Under the load of Smackover carbonates, deformation of salt is widespread and well imaged by seismic data (e.g. Figure 2-3; Bally, 1981; Wu et al, 1990a). The typical "salt roller" (e.g. Figure 1-5, Line B in Figure 2-3; Bally, 1981) structures are formed by carbonate blocks sliding on top of the deformed salt in a gently dipping shelf setting. The extension of the Smackover is accommodated by the basinward flow of the Louann salt. The Smackover deformation ceased by the Late Jurassic over most of the platform area (e.g. Figures 1-5 and 2-3), because much of the thin salt on the platform was squeezed out, i.e. evacuated to move basinward under the Smackover load.

As a result of the basinward salt movement, the deformation of the Late Jurassic section (Cotton Valley) occurs much further basinward relative to the earlier deformation (e.g. Figure 2-3). The "salt rollers" involving the Smackover interval were not reactivated by the thick Late Jurassic Cotton Valley. However, the peripheral faults seem to be active beyond the Upper Cretaceous (e.g. Figure 1-5). These peripheral faults develop near the updip limit of the mid-Jurassic salt (Figure 1-5 and Map 2). On Figure 2-3, we can see this progressively basinward shifting of deformation as a consequence of salt movement under the sediment wedge. The great expansion of Late Jurassic sediments shown in Figure 2-3 suggests the involvement of salt. The Late Jurassic section is actively involved in salt deformation. This section thins across the shelf margin as shown by Figure 1-5 and Line B in Figure 2-3.

During the Lower Cretaceous, thick carbonate platforms developed around the Gulf of Mexico Basin (Figure 4-2, Cook and Bally, 1975; McFarlan and Menes, 1991). Note again in Figure 2-3 that much of the Lower Cretaceous section remains undeformed on the platform although it is underlain by the mid-Jurassic highly deformed Smackover except for the Destin Dome. Because by early Cretaceous time, Louann salt was mostly
situated in the slope area, we would expect salt-related deformation during the Lower Cretaceous section in the Cretaceous slope area which is precisely what I see on the seismic data.

4.2. Pre-mid-Cretaceous deformation on the slope

The regional seismic profiles (D1-D35, S1-S9 in Plates I-VIII) give us an overview of the deformation in the slope area. The post-salt and pre-mid-Cretaceous (150.5-91.5 Ma) sediments are highly deformed. The style of structures on slope differs substantially from the salt rollers and faulted and rotated blocks observed in the Smackover section on the shelf. Rather than a series of rotated blocks I now observe that in the slope area "pseudo-clinoforms" (Wu et al, 1990b), "turtle structures" and other syndepositional structures dominate. This change in structural style is perhaps due to a thicker salt layer, a less accentuated basement slope and the Lower Cretaceous ductile slope sediments that perhaps deform relatively more easily in response to the salt movement than the rigid Late Jurassic Smackover shelf carbonates. The salt movement in the slope area during pre-mid-Cretaceous time greatly influenced the deposition of the sediments. Map 3A is an isopach of the Upper Jurassic-middle Cretaceous (150.5-91.5) interval. Local thickness variations indicate the thickness changes or salt evacuation patterns by mid-Cretaceous time (Wu et al, 1990b). In other words, thick areas coincide with evacuated area (turtles structures) and thin areas indicate growing salt structures. The thickness changes in the salt province contrast with the stable isopachs over the salt-free area and illustrate that salt movements during the late Jurassic-mid-Cretaceous interacted actively with sedimentation. Localized thick sections became turtle and half turtle structures as flanking salt moved upward during the Neogene.
Seismic examples shown in Figures 2-7, 8, 9 and 4-3, 4, 5 and 6 from the slope area show some typical seismic expression of the pre-mid-Cretaceous deformation related to salt movements. Figure 4-7 (from Wu et al, 1990b) shows the development of the pseudo-clinoforms. The deformation of salt due to differential loading occurred in response to the sediment load and in a feedback system as the sediments themselves were deformed. This interaction continued until the autochthonous salt is completely evacuated to form salt diapirs. The sediments overlying the salt are welded to the base of the salt when salt is totally evacuated, and structures cease to grow (e.g. Figures 4-3, 4-4, 4-5). This is reflected by the style of deformation within the thick pre-mid-Cretaceous interval. The relatively undeformed overlying Tertiary sediments above the highly deformed pre-mid-Cretaceous section indicate that the structures ceased to grow by mid-Cretaceous time, because there was no more salt available to be drained into the structures. In contrast, in the areas underlain by salt where the upper Jurassic-mid-Cretaceous was relatively thin, the Tertiary overburden was deformed by the late Tertiary salt movements. By the end of mid-Cretaceous there were areas with highly deformed and welded sections and areas with little or no salt deformation.

4.3. Mid-Cretaceous allochthonous salt

Some of the salt that was pushed basinward in front of the sediment load was trapped under a thick sediment load. These trapped salt bodies were driven by buoyancy forces and pierced through the overburden to form the earliest allochthonous salt bodies of the northeastern Gulf of Mexico. Regional seismic profiles D1-D4, S1-S2 and seismic examples Figures 2-3, 2-7, 2-8 and 4-6 illustrate some of these minor but characteristic mid-Cretaceous allochthonous salt bodies. The seismic data clearly show that large parts of these salt bodies are overlying the late Cretaceous section. Thus by definition they are
Note: Figure 4-3a is included in the pocket together with the plates and maps.
Note: Figure 4-3b is included in the pocket together with the plates and maps.
Note: Figure 4-4a is included in the pocket together with the plates and maps.
Note: Figure 4-4b is included in the pocket together with the plates and maps.
Note: Figure 4-5a is included in the pocket together with the plates and maps.
Note: Figure 4-5b is included in the pocket together with the plates and maps.
Figure 4-6b. An interpreted NW - SE seismic example of Mid-Cretaceous allochthonous salt bodies. See Figure 4-1 for location of seismic line. A well imaged and almost undeformed mid-Cretaceous allochthonous salt body is shown. The allochthonous salt shown was emplaced during mid-Cretaceous to Paleogene before MO time. The shaded area is salt. See Plate IX for the age of correlated surfaces.
Figure 4-7. Development of pseudo-clinoforms (after Wu, Bally, Cramer, 1990). Note that the asymmetric loading before mid-Cretaceous pushed salt basinward. Pseudo-clinoforms formed within overburden as a result of the salt withdrawal.
allochthonous in nature (see glossary). Some of them are reactivated during the Miocene (e.g. Figure 2-8). The onlap patterns over some undeformed mid-Cretaceous allochthonous (e.g. Figures 2-3, 2-7, 2-8) salt bodies indicate that they emplaced mostly before 91.5 Ma and some during 91.3-30 Ma interval (e.g. Figure 4-6). The mid-Cretaceous allochthonous salt bodies are found only in the northeastern and southeastern corners of the studied slope area where the pre-mid-Cretaceous section is thick. No allochthonous salt bodies are found on the Lower Cretaceous shelf.

4.4. Mid-Cretaceous salt distribution

By the end of mid-Cretaceous time, starved sedimentation in the slope area followed Turonian transgression (91.5 Ma, Haq, et al, 1987) and its corresponding lack of siliciclastic sediment input in northern Gulf of Mexico (e.g. Figure 2-10, Figure 4-2B, Cook and Bally, 1975; Sohl et al, 1991). From mid-Cretaceous (Turonian, 91.5 Ma) to mid-Oligocene (30 Ma), most of the present slope areas were starved (Figure 2-10, Map 9; Sohl et al, 1991; Galloway, 1991; Salvador, 1991b). Sediment starvation lasted longer in the northeastern Gulf of Mexico than in the western and northwestern Gulf of Mexico. The prominent "MCU" ("Middle Cretaceous Unconformity" e.g. Buffler, 1983) seismic reflector is interpreted to be the seismic response of the condensed section following the Turonian (91.5 Ma) sea-level high and was renamed "Middle Cretaceous Flooding Surface (MCFS) " (Plate IX; Wu et al, 1990a). As a result of the starved sedimentation, salt-related structures remained dormant on the slope during the entire mid-Cretaceous-mid-Oligocene period.

The prolonged inactivity of salt structures enables me to estimate the relative distribution of salt around mid-Cretaceous time (Wu et al, 1990b). On the Upper-Jurassic (150.5 Ma) -mid-Cretaceous (91.5 Ma) Isopach (Map 3A), excluding the salt-free area,
the relatively thick isopach corresponds to primary welds or thin salt. The thin isopach represents an area occupied by relative thick salt massifs at that time. This relationship is well illustrated in Figure 4-7(e). Map 3B shows the mid-Cretaceous distribution of salt on slope derived from the Isopach Map 3A, which assumes a relatively smooth and gentle sea floor and basement at mid-Cretaceous time. From the estimated salt distribution on Map 3B, we can see that over most of the slope area there is much salt with dramatic thicknesses changes ranging from zero to more than four kilometers. I refer to the large concentrated salt mass as salt massifs. Most of the upper slope is welded or with very thin salt as shown on the regional profiles D1-20, S1-S9 and seismic examples Figures 2-7, 2-8, 2-9, and 4-3, 4-4, 4-5, and 4-6. The relationship between the postulated mid-Cretaceous salt distribution and the distribution of present allochthonous salt is documented by Map 3B and seismic examples. The distribution of the mid-Cretaceous salt pre-determines the configuration of the allochthonous salt tongues formed mainly during the Neogene. Thus these salt massif concentrations later evolved to form large allochthonous salt systems.

4.5. Discussions and summary

The mid-Jurassic Louann salt was deformed by sediment loads during late Jurassic to mid-Cretaceous time. The deformation of salt and sediments progressed basinward as sediments prograded over the salt into the basin. Jurassic deformation is limited to the updip edge of the salt basin and below the Cretaceous shelf where peripheral systems and extensive salt rollers formed. The peripheral fault systems lasted into the Cretaceous. The Jurassic salt rollers and rotated slabs ceased to develop by the late Jurassic because most of the salt was evacuated. Since the early Cretaceous, salt deformation largely concentrated in the slope area. Structures such as "pseudo-clinoforms" and "turtle
structures" are typical for the slope and record salt movements. Under the sediment load, salt concentrated to form large salt massifs with a thin sediment cover, domes, anticlines and occasionally some allochthonous salt bodies in the slope area.

By the mid-Cretaceous, much of the salt under the Cretaceous shelf and upper slope became thin or was evacuated to form primary welds. Originally widespread Louann salt was concentrated in the slope area to form large salt massifs in various forms. The distribution of the mid-Cretaceous salt structures influenced the location and extent of the allochthonous salt bodies that subsequently formed in response to Neogene sediment loads. Extensive primary welds formed under the Lower Cretaceous shelf and upper slope.
Chapter Five

Mid-Cretaceous to Mid-Oligocene Stabilization of Structures

Following the Turonian transgression (Haq, et al, 1987), as already discussed in Chapter Two, the depocenters of Late Cretaceous - Paleogene were located in the western part of the Gulf of Mexico (Figure 2-10; after Salvador, 1991a, 1991b; McFarlan and Menes, 1991; Sohl et al, 1991; Galloway et al, 1991). In contrast, our area received very little sedimentation (Map 9). The rate of sedimentation during this period was very low (Figure 2-11).

Salt deforms in response to sediment loading. As shown earlier on Map 3B, by mid-Cretaceous most of the salt was concentrated in the salt massifs below the slope area. Salt structures formed by the mid-Cretaceous remained stable during this extended period of starved sedimentation. No major salt movement occurred during the Late Cretaceous-Paleogene in the northeastern Gulf of Mexico as shown by the relatively monotonous mid-Cretaceous (91.5 Ma) -mid-Oligocene (30 Ma) thickness shown on regional profiles D1-D35, S1-S9 and on time-thickness Map 9. The development of some minor mid-Cretaceous allochthonous salt continued during this time interval (91.5-30 Ma).

Although most of the slope area is structurally quiet, the Destin Dome (Figures 1-3 and 1-5) developed during this period (91.5-30 Ma). Much of the formation of the Destin Dome occurred from the late Early Cretaceous to Paleocene as shown on Figure 1-5. Salt within the main part of the Destin Dome never pierced through the overburden (e.g. Figure 1-5; MacGrae, 1990). This is perhaps due to the strength of the overlying platform carbonates and a relatively small amount of salt as compared with the slope. This contrasts with what we observed about salt deformations on the slope where salt apparently deforms its overburden and forms large amounts of allochthonous salt at shallow depths.
The structurally quiet period during mid-Cretaceous-mid-Oligocene (91.5-30 Ma) contrasts to the structurally active intervals before and after as illustrated in Table 5-1. This interval separates two structurally distinct periods in the slope area of the northeastern Gulf of Mexico.

Table 5-1 Major Meso-Cenozoic tectonic events in the northeastern Gulf of Mexico and the subjects discussed in Chapter Five. The crustal types of the basement are adapted from Buffler (1989) and Salvador (1991b).
Chapter Six

Neogene Development of Allochthonous Salt

By mid-Oligocene time when the sea-level fell globally (Figure 2-6, Plate IX, Haq, et al. 1987), the depocenters of the Gulf of Mexico began to shift eastward (Figure 2-10, Winker, 1982; Galloway et al., 1991; Salvador, 1991a). In the study area a renewed stage of salt deformation began under the load of rapidly prograding sediments. The structures developed since mid-Oligocene are summarized in Table 6-1.

Table 6-1 Major Meso-Cenozoic tectonic events in the northeastern Gulf of Mexico and the subjects discussed in Chapter Six. The crustal types of the basement are adapted from Buffler (1989) and Salvador (1991b).
6.1. Distribution and morphology

Allochthonous salt and welds of various stages occur south and west of the mid-Cretaceous shelf margin and underlie the lower continental slope of the northern Gulf of Mexico. Figures 1-3 and 6-1 show the distribution of allochthonous salt and Maps 6 and 7 show the salt thickness (in time) and structure (in time) of the allochthonous salt for the study area. Dip and strike sections on Plates I-VIII show the cross sectional view of typical allochthonous salt structures across the study area. Allochthonous salt covers most of the slope. These salt tongues are located south of the Lower Cretaceous shelf margin and terminate to form the Sigsbee Escarpment (Figure 1-1 and Map 1). Most of the allochthonous salt bodies are located to the north of the Mississippi Fan Fold Belt. Only minor allochthonous salt bodies form over the Mississippi Fan Fold Belt.

To the east, allochthonous salt bodies are discrete and small as shown in Figure 1-3, Maps 1, 6, and 7. The outline of individual allochthonous salt bodies is clear and shown on Plate I. Many of these allochthonous salt bodies still appear to be attached to their feeder stocks. These asymmetric and newly emplaced allochthonous salt bodies form bathymetric highs on the sea floor as shown on Map 1. They are elongated in the downdip direction indicating that salt spread downslope under gravity as it was emplaced just below the sea floor. The allochthonous salt tongues widen toward the west and south and eventually coalesce to form larger composite salt sheets. The progressive change of shape of the allochthonous salt is documented by cross-sections on Plates II and III and Maps 6 and 7. Allochthonous salt sheets below the upper slope are further deformed by post-emplacement sediment loads. The bathymetric highs associated with the newly emplaced allochthonous salt disappear. The original salt feeders are evacuated and secondary welds are formed as illustrated in the cross sections D9-D12 on Plate II. Secondary withdrawal basins form on top of the widely spread out allochthonous salt sheets. Some tertiary welds (see Appendix I for definition) form when the primary allochthonous salt is evacuated (e.g.
Figure 1-5). Salt sheets became more deformed and spread farther downslope in the western part of the study area as shown in the cross sections on Plates IV-VI. The allochthonous salt sheets spread downslope to form the sea floor scarp - Sigsbee Scarp as shown on Map 1 and Figure 1-1.

Extensive tertiary welds form when the allochthonous salt (Figure 1-5, Map 6 and Plates IV-V) is evacuated in response to supra-allochthonous-salt sediments that displace salt. Secondary allochthonous salt (see Appendix I for definition) tongues develop as thick sediments rapidly build up on top of the primary allochthonous salt. The development of supra-allochthonous-salt diapirs and secondary allochthonous salt tongues creates strong bathymetric relief (Map 1, D33-D35 on Plates VI, S4 and S5 on Plate VII). As the secondary allochthonous salt structures form, large supra-allochthonous-salt withdrawal basins or secondary withdrawal basins (see I for definition) form on the present continental slope as illustrated on Map 1. Seni (1991) documented some of the supra-allochthonous-salt basins in the Green Canyon area using 3-D seismic data. Map 8 shows that the thickness (in time) of supra-allochthonous-salt sediments varies greatly. The depocenters are associated with tectonically thinned allochthonous salt and tertiary weld areas. The relationships between primary and secondary allochthonous salt structures and associated supra-allochthonous-salt basins are shown on Map 7 and in cross sections on Plates V-VI. The transition from incipient to highly advanced allochthonous salt as we proceed from east to west is documented on strike sections S1-S8 of Plates VII-VIII. Landward, the increased deformation of the allochthonous salt sheet by large supra-allochthonous-salt loads is shown on the dip profiles D1-D35 of Plates I-VI. Regional thickness changes and the shape and distribution of the allochthonous salt are also shown on Maps 6 and 7.

In summary, the allochthonous salt is progressively more deformed in a landward and westward direction. Individual allochthonous salt bodies are more spread out and contiguous in the downslope direction. Supra-allochthonous salt domes and diapirs and
secondary allochthonous salt tongues form on top of the primary allochthonous salt as sediment loads increase. Large primary withdrawal basins form as salt withdraws from the mother salt to form primary allochthonous salt sheets. The secondary and tertiary withdrawal basins form on primary and secondary allochthonous salt as rapid sedimentation continues. Bathymetric highs are formed over the active primary and secondary allochthonous salt structures. Bathymetric lows form over the salt withdrawal basins on top of the less active portions of the primary and the secondary allochthonous salt. Weld systems of various stages (primary to quintic, e.g. Figure 1-5) develop under increased sediment loads.

6.2. Reactivation of pre-existing salt structures

After nearly sixty million years of condensed sedimentation, the Late Oligocene and Lower Miocene depocenters shifted eastward (Figure 2-10, Winker 1982; Galloway et al, 1991; Salvador, 1991b). A rapid increase of sediment thickness in the northwest corner of the Mississippi Canyon is observed for the mid-Oligocene to Lower Miocene interval. On Map 11, we can see that the thickest isochron is over 2 seconds (two way time) or over 3,400 meters (assuming an approximate interval velocity of 3,400 meter/second) in the northwest part of the Mississippi Canyon area. As shown on Map 11, the isochrons vary greatly in contrast to the mid-Cretaceous to mid-Oligocene interval shown in Map 9. Local thickness increases are particularly strong in the Mississippi Canyon area. These thickness changes reflect accommodation variations to the deformation of the underlying salt. The thickness changes of mid-Oligocene-Lower Miocene can also be seen on the regional profiles D5-D20 and S1-S6.

The reactivation of the salt structures is recorded in the sedimentary section by the above mentioned local thickness changes of the mid-Oligocene-Lower Miocene interval.
Regional profiles D1-D20 and seismic examples Figures 4-4, 5 and 6 and Figure 6-2 show these thickness changes of the mid-Oligocene-Lower Miocene interval. During this period, the autochthonous salt structures began to grow again but remained attached to their roots over most of the study area. Most of the allochthonous salt structures began to form later and above the Lower Miocene (15.5 Ma) surface. During the mid-Oligocene-Lower Miocene (15.5 Ma), the deformation of salt is associated with some extension. In the Mississippi Fan Fold Belt area, the thickness of this interval changes little.

In summary, the salt structures formed before mid-Cretaceous were reactivated by the increased sediment load during the mid-Oligocene (30. Ma) - Lower Miocene (15.5 Ma). Extension during this period is accommodated by the deformation of the underlying salt. The shortening in the Mississippi Fan Fold Belt occurred later.

6.3. Active diapirism and related structures

The rate of sedimentation increased rapidly since the Lower Miocene (Figure 2-11). By the end of Middle Miocene (10.5 Ma), thick sediments covered most of the area as shown on Map 12. The Middle Miocene sediments reach a time-thickness in excess of 3 seconds (two way reflection time) or more than 4,800 meters (using a 3,200 m/second interval velocity) in some local depocenters in the Mississippi Canyon area (Map 12). The depocenter shifted farther eastward as also shown on Figure 2-10. The rate of sedimentation in local depocenters during the Middle Miocene (4,800 m in 5 million years or 960 m/Ma) is more than three times higher than the rate of the mid-Oligocene-Lower Miocene interval (3,200 in 15 million years or 213 m/Ma). The increase of sedimentation rate is also shown on the typical rates of sedimentation of Figure 2-11.

In response to this rapid increase of sedimentation, three major Middle Miocene (15.5-10.5 Ma) events are illustrated by reflection seismic profiles and maps. First, salt
Figure 6-1. Index map for seismic examples in Chapter Six.
Note: Figure 6-2a is included in the pocket together with the plates and maps.
Note: Figure 6-2b is included in the pocket together with the plates and maps.
Note: Figure 6-3a is included in the pocket together with the plates and maps.
Note: Figure 6-3b is included in the pocket together with the plates and maps.
diapirs grew upward rapidly. Second, several local depocenters were formed to fill the primary salt withdrawal basins of the Mississippi Canyon and northern Atwater Valley areas (Map 12). Growth fault systems continued to form around the salt withdrawal basins mostly landward of the large allochthonous salt structures (e.g. Figures 4-6 and 6-2a). Third, the Mississippi Fan Fold Belt formed along the basinward edge of the mid-Jurassic salt basin. In terms of tectonism, this period is particularly active compared to the earlier post-salt tectonic history.

The rapid growth of the salt structures is well illustrated by the Middle Miocene thickness changes (Map 12). In general, over most of the study area, the Middle Miocene (see regional profiles D1-D20 in Plates I-IV) thins tectonically, reflecting the growth of these salt structures. Before and after the Middle Miocene, the thinning against salt structures is not as pronounced suggesting that during the Middle Miocene the salt structures grew mostly upward through active diapirism (see Appendix I for definition). Active diapirism is caused by rapid differential and massive sediment loading (Figures 2-10 and 2-11, Map 12) on top of pre-existing salt massifs. Before this period of active diapirism, most of the salt structures (i.e. large salt massifs and pillows) were already covered by a varying thickness of sediments. The overburden was over 2 km thick which was enough for salt to pierce through overlying sediments. Most of the hypothetical diapiric feeder systems are not easily mappable with conventional seismic data. As shown by some of the visible feeder stocks (e.g. D4-D12, D16-D18) and our previous study (Wu et al, 1990b), the diapiric salt feeders served to transfer autochthonous salt to eventually form allochthonous salt rising close to sea floor. Thus we can conclude that diapirs rose from autochthonous salt during the Middle-Late Miocene and at least one feeder system corresponds to each allochthonous salt body.

As a consequence of the rapid growth and development of salt diapirs, primary withdrawal basins are filled by a thick accumulation of sediments as shown on Map 12.
The amount of lateral salt movement during the Middle Miocene is limited and most salt structures are still rooted. The amount of salt mobility reflected by the diapiric salt structures is less than that the mobility related to the formation of allochthonous salt structures. A number of minor growth faults developed and continued to develop around some of the large withdrawal basins (e.g. S7, S9, S10 and S11). Most of the sediments over the withdrawal basins deformed without severe faulting (e.g. Figures 4-4 and 4-5), i.e. sediments deformed in a ductile manner.

One of the most interesting features that developed during the Middle Miocene is the Mississippi Fan Fold Belt. I would like to emphasize that a) the fold belt is contemporaneous with the actively rising diapirs just described; b) The fold belt is formed along the southern edge of the mid-Jurassic salt; c) Sparse coeval extensional faults occur updip from the folded belt; d) The fold belt is short-lived and ceased to be active by the Middle Miocene (10.5) in the western part and Late Miocene (5.5 Ma) in the eastern part of the fold belt.

These observations raise several questions about the genesis of the Mississippi Fan Fold Belt. What initiated the fold belt? What is the relation of Middle Miocene diapirism to the formation of the Mississippi Fan Fold Belt? How much did the updip extensional faulting contribute to the shortening of the fold belt? What was the controlling mechanism that abruptly terminated the shortening of the fold belt even though the sedimentation increased since the initiation of the fold belt? I will discuss possible answers to these questions in Chapter Eight after looking at more data from the Mississippi Fan Fold Belt in Chapter Seven.
6.4. Spreading of allochthonous salt and development of related structures

Following the diapiric stage, the diapiric salt structures served as salt feeders (see Appendix I for definition) through which salt moved from the mother salt almost to the floor to form large downslope spreading allochthonous salt structures on the continental slope (see regional profiles D1-D20). These allochthonous salt tongues are relatively sparse in the east but become more widespread in the western part of my area as shown on Map 6 and the regional seismic profiles D1-D35 and S1-S9. The spreading of the allochthonous salt occurred mostly during the late Middle Miocene to the early Pliocene and shifted from the west to the east in response to the eastward shift of the depocenters. Large amounts of salt rose from the autochthonous diapirs to form the allochthonous salt structures. An abundant supply of salt was available to form the large scale allochthonous salt structures on the continental slope. As we see on the regional profiles (Plates I-V), most allochthonous salt structures are asymmetric with respect to their feeder stocks or walls, i.e. the salt allochthons spreads in a downdip direction. Thus as salt rises close to the sea floor, it spreads along the regional or local slope. Map 6 also shows that allochthonous salt tongues widen in the downdip direction.

During the Late Miocene allochthonous salt spreading, primary withdrawal basins formed landward of the allochthonous salt structures as shown on Map 13. From the time-thickness Map 13, we can see that the structural activity was not as severe as during the Middle Miocene. An explanation is that during the Late Miocene the rate of the sedimentation slowed down (Figure 2-11) and the allochthonous salt structures are mostly spreading laterally near sea floor. Most of the sediments are accumulated in large primary withdrawal basins updip and behind the allochthonous salt.

By the end of Late Miocene, large amounts of the diapiric salt moved to a shallow section to form more allochthonous salt. As the salt moved away from the mother salt, large primary welds formed. Large turtle structures formed when the withdrawal basins
were inverted as salt of previous salt structures moved away (e.g. Figure 6-4). A series of
tensional faults affects the Late Miocene surface over turtle structures or quasi-turtle
structures. Most of the faults shown on Map 16 are tension faults. These shallow faults
extend laterally over a short distance. Also some growth faults formed updip from the
feeder stock or diapirs. The extension by these faults is accommodated by the thinning of
the feeder stocks or walls (e.g. D9, D10 and D11 show extension of growth faults
accommodated by thinning of the original salt feeder). A secondary weld formed when the
feeder was completely evacuated. As soon as salt is depleted, the associated withdrawal
basin and growth faults cease to develop. This is typical since the Late Jurassic.

By the Pliocene, most of the deep seated autochthonous salt had been transferred to
the shallow Miocene-Holocene allochthonous system (e.g. Figure 6-5) responding to thick
differential slope sediment loads. Most of the remaining autochthonous salt of the study
area remains in the Destin Dome area and underneath the Mississippi Fan Fold Belt. Much
of the original salt layer landward to and underneath the allochthonous salt system was
squeezed out forming a primary weld.

6.5. Secondary allochthonous salt structures

Massive sedimentation continued after the emplacement of allochthonous salt.
Thus, during the Late Miocene, the Mississippi Delta began to shed massive amounts of
sediments into the study area. The rate of sedimentation increased significantly since
Pliocene (Figure 2-11, Maps 13, 14 and 15). As discussed earlier, the primary withdrawal
basins ceased to develop when the autochthonous salt and feeder salt was depleted.
Therefore these basins could no longer accommodate the increased sedimentation of the
Pliocene. Thus, these sediments were deposited over the allochthonous salt. As shown on
Map 14, most of the Pliocene was deposited over the allochthonous salt. The lateral
Note: Figure 6-4a is included in the pocket together with the plates and maps.
Note: Figure 6-4b is included in the pocket together with the plates and maps.
Note: Figure 6-5a is included in the pocket together with the plates and maps.
Note: Figure 6-5b is included in the pocket together with the plates and maps.
variation of the isochron illustrates the Pliocene supra-allochthonous-salt basins or secondary withdrawal basins. Allochthonous salt deformed swiftly under deltaic loading. The longer the differential loading the more profound the allochthonous salt deformation.

Regional seismic profiles S1-S8 illustrate the increased deformation of allochthonous salt from east to west. Map 7 shows structure on the top of the allochthonous salt in two way time. The allochthonous salt in the west and north is particularly deformed. As the allochthonous salt is deformed and thinned, tertiary welds form when the primary allochthonous salt is evacuated. Map 6 shows the thin salt (less then 200 ms) and welds joining strata that were separated by allochthonous salt. Large depocenters or supra-allochthonous-salt basins form over the thinned allochthonous salt. Map 8 illustrates the total sediment thickness over the allochthonous salt. As much as 7 seconds in thickness (two way reflection time) of sediments are deposited over the allochthonous salt of the Green Canyon area.

As thick sediments are loaded on top of the allochthonous salt, salt deforms and moves away from the depocenters. Map 6 and the regional profiles D19-D35 show that most of the allochthonous salt accumulates in front of the thick sediment loads. However, there are new salt structures overlying and evolving from the previously emplaced allochthonous salt as shown on regional profiles D26, D27, D31-D35 and on seismic examples in Figures 6-6 and 6-7. These second generation allochthonous salt structures are "secondary allochthonous salt structures" that evolve from the primary allochthonous salt. The transition from primary to secondary allochthonous salt is well illustrated by regional profiles S3-S6 and is also shown on Map 7 of the top of the allochthonous salt.

From the evolution of the primary and secondary allochthonous salt we can see that salt deforms to adjust its position on the slope to dynamically reduce the potential energy of the entire system. Similar to the formation of primary and secondary allochthonous salt, third or even fourth generation allochthonous salt sheets may evolve when the
Figure 6-6a. An uninterpreted NW - SE seismic example of a secondary allochthonous salt tongue and associated withdrawal structures. See Figure 6-1 for location of seismic line.
Figure 6-6b. An interpreted NW-SE seismic example of a secondary allochthonous salt tongue and associated withdrawal structures. See Figure 6-1 for location of seismic line. Tertiary wells are shown. The correlated stratigraphic surface is PL-Pliocene (1.9 Ma). The shaded area is salt.
Note: Figure 6-7a is included in the pocket together with the plates and maps.
Note: Figure 6-7b is included in the pocket together with the plates and maps.
sedimentation continues. We already observe local basins form on top of the secondary allochthonous salt namely "tertiary withdrawal basin"(e.g. D31, Figure 6-7). Further evacuation of salt from secondary feeder and salt tongues led to the formation of quaternary and quintic welds (Figure 1-5). The sea floor is highly deformed by contemporaneous allochthonous salt deformation in the Green Canyon area (see Map 1). Most of this deformation is related to the secondary allochthonous salt formation.

6.6. Summary

Salt structures formed before mid-Cretaceous were reactivated by the mid-Oligocene-Lower Miocene sediment influx after being dormant for nearly 60 million years. Rapidly accumulated sediments of mid-Oligocene-Middle Miocene led to a density inversion situation between salt and unevenly distributed overlying sediments. Active diapirism driven by buoyancy provided the path of salt movements from an autochthonous mother salt to allochthonous salt tongues and sheets on the continental slope of the northeastern Gulf of Mexico. No regional extension is observed for the period prior to the massive diapirism of salt during the Middle Miocene. The spreading of allochthonous salt downslope occurred since Late Miocene. The allochthonous salt was further deformed under continued sedimentation. Some secondary allochthonous salt formed in the Green Canyon area over the primary allochthonous salt because of renewed thick sediment accumulation. The sea floor is deformed by the contemporaneous allochthonous salt deformation. As salt of different stages moved from one place to another, primary, secondary and tertiary withdrawal basins formed. Primary to quintic welds formed when salt was evacuated from its position.
Chapter Seven

Mississippi Fan Fold Belt

The evolution of the contractional Mississippi Fan Fold Belt is one of the most intriguing problems of the tectonic history of the northeastern Gulf of Mexico. This is so because a) it is developed on a passive margin; b) It extends in a narrow band relative to extensive extensional domain; c) It appears short-lived from the Middle Miocene to Late Miocene; and d) It is not directly related to various extensional growth fault systems updip either in time or in space. I try to document my observations with regional reflection seismic profiles calibrated by my sequence stratigraphic framework. Some possible models for the initiation and cessation of the fold belt are offered later in Chapter Eight. Table 7-1 shows the context of the subjects to be discussed in this chapter.

7.1. Location and extent

The NE-SW trending Mississippi Fan Fold Belt is located on the lower slope of the northeastern Gulf of Mexico (see Figures 1-3 or 7-1). It is situated along the basinward edge of the mid-Jurassic salt basin. Toward the north and the landward limit of the mid-Jurassic salt basin, there are widespread extensional systems of various ages and extent as well as widespread allochthonous salt structures on the upper and middle slope. To the south mostly undeformed deep-water sediments overlie a salt-free oceanic basement as illustrated on regional profiles D2-D29 on Plates I-V.

The Mississippi Fan Fold Belt extends from the Walker Ridge area to the southwest corner of the De Soto Canyon area as shown on Map 10, which is the time-structure map of the mid-Oligocene (30 Ma). The fold belt extends for about 350 km from the southwest to the northeast. The width of the mappable part of the northeastern fold belt is about 40
Table 7-1 Major Meso-Cenozoic tectonic events in the northeastern Gulf of Mexico and the subjects discussed in Chapter Seven. The crustal types of the basement are adapted from Buffler (1989) and Salvador (1991b).
Figure 7-1. Index map for seismic examples in Chapter Seven.
Note: Figure 7-2a is included in the pocket together with the plates and maps.
Note: Figure 7-2b is included in the pocket together with the plates and maps.
Figure 7-3a. An uninterpreted NW - SE seismic example of the Mississippi Fan Fold Belt across well Shell #1, Atwater Valley 471. See Figure 7-1 for location of seismic line.
Figure 7-3b. An interpreted NW - SE seismic example of Mississippi Fan Fold Belt across well Shell #1, Atwater Valley. See Figure 7-1 for location of seismic line and Figure 2-2 for well location. The shortening occurred during MM1-UM. The top of the fold is also eroded. Sandy intervals are observed in the Middle Miocene sediments in the well. Most of the reverse faults verge to the south. See Plate IX for the correlated surfaces.
Note: Figure 7-4a is included in the pocket together with the plates and maps.
Note: Figure 7-4b is included in the pocket together with the plates and maps.
Figure 7-5a. An uninterpreted NW - SE seismic example of a peneplained thrust from the western part of the Mississippi Fan Fold Belt. See Figure 7-1 for location of seismic line.
Figure 7-5b. An interpreted NW - SE seismic example of a peneplained fault propagation fold from the western part of the Mississippi Fan Fold Belt. See Figure 7-1 for location of seismic line. The shortening in this part of the Mississippi Fan Fold Belt ended by MM3 as shown by the unconformity. The fold shown was severely eroded. More than about 2 km of the thrust was eroded. Most of the MO-LM section and all of the Middle Miocene sections of the thrust were eroded in a deep-water environment (> 2,000 m water depth). The shaded area is salt. See Plate IX for the age of the correlated surfaces.
Note: Figure 7-6a is included in the pocket together with the plates and maps.
Note: Figure 7-6b is included in the pocket together with the plates and maps.
km. Relative to the extensional systems, the Mississippi Fan Fold Belt forms a narrow band which is less than one-eighth the width of the extensional systems.

7.2. Timing and structure of the Mississippi Fan Fold Belt

The age of the Mississippi Fan Fold Belt varies from west to east as shown on Figures 7-2, 3, 4, 5, and 6 (see Figure 7-1 for locations). Figure 7-2 across the eastern fold belt shows that tectonic thinning in the fold belt occurs mostly between 12.5 Ma and 5.5 Ma. The 5.5 Ma angular unconformity is overlain by undeformed Pliocene-Present sediments and marks the end of shortening in the fold belt. Thus the shortening in the eastern part of the fold belt occurred during the middle Middle Miocene (13.8 Ma) to Late Miocene (5.5 Ma).

Figure 7-6 across the western part of the Mississippi Fan Fold Belt shows that the tectonic convergence began after 15.5 Ma and ended by 10.5 Ma. The 10.5 Ma angular unconformity is overlain by more than 2.5 seconds (two way time) of the undeformed sediments and marks the end of compression in the western part of the fold belt. Therefore the shortening to the west occurred during the Middle Miocene between 15.5 and 10.5 Ma (about 5 million years). The examples from the eastern and western part of the fold belt show that the fold belt as a whole was active during the Middle-Late Miocene (15.5 to 5.5 Ma). The shortening occurred earlier in the west (15.5-10.5 Ma) and later in the east (12.5-5.5 Ma). This progressively younger-to-the-east relationship coincides with the eastward shift of sedimentation and can be seen on a single regional strike profile (S7 in Plate VIII).

The map of the mid-Oligocene (Map 10) shows the structure of the Mississippi Fan Fold Belt. Most of the thrust faults are basinward verging (e.g. Figures 7-2, 3 and 5). Only a few of the thrust faults are verging to the north (e.g. Figure 7-6). Figure 7-4 shows both
NW and SE verging thrust faults. Generally speaking, the shortening in the Mississippi Fan Fold Belt is minimal and in the order of 2-3 km or less, as illustrated by regional seismic profiles D2-D29 and the seismic examples Figures 7-2 to 7-6.

The seismic data across the Mississippi Fan folds confirm that the Mississippi Fan Fold Belt is cored by mid-Jurassic autochthonous salt (see regional profiles D2-D29). Some of the salt in the core of the folds squirts up to form small scale allochthonous salt bodies as shown on Map 10. On Figure 7-2 we can see a small allochthonous salt tongue just beginning to form with a feeder still connecting it with the autochthonous salt. Figure 7-7 shows an allochthonous salt body that formed just below the sea floor during the Holocene to become the Green Knoll sea floor high. Seismic example Figure 7-6 shows the thrusts in the area of the Green Knoll allochthonous salt. The relationship of a fold to the overlying allochthonous pod is best seen on seismic example Figure 7-8. It shows that the fold and its salt core formed during the Middle Miocene. The salt core squirted out from the anticline and emplaced very recently (Holocene) near sea floor. Koyi (1988) conducted some scaled experiments to show the role of gravity and lateral shortening in the Zagros Mountain belt of Iran. There are some similarities between his experimental results and the mapped distribution of allochthonous salt in the Mississippi Fan Fold Belt (Map 10). He also concluded that post-shortening diapirs are more common in the anticlines.

7.3. Summary

The Mississippi Fan Fold Belt formed during the Middle Miocene (15.5-10.5 Ma) in the western end of the fold belt and developed later during the middle Middle Miocene-Late Miocene (13.8-5.5 Ma) in the eastern part of the fold belt. It was not reactivated despite increased updip sediment deposition during the Pliocene-Present period. The fold
Figure 7-7b. An interpreted NW - SE seismic example across Greens Knoll. See Figure 7-1 for location of seismic line. This line is parallel and next to Figure 7-7b. The Green Knoll sea floor high is uplifted by a detached salt diapir that squirmed from the salt core of the Mississippi Fan Fold Belt under Late Miocene-present sediment loads. The top of the allochthonous salt is very close to sea floor. The shaded area is salt. See Plate IX for the age of the correlated surfaces.
Figure 7-8a. An uninterpreted NE - SW seismic example across the Green Knoll and its associated fold. See Figure 7-1 for location of seismic line.
Figure 7-8b. An interpreted NE - SW seismic example across the Greens Knoll and associated fold. See Figure 7-1 for location of seismic line. It is clearly shown that the detached salt diapir was developed from the core of the fold. The detached diapir formed very recently as shown by the deformed sea floor. The shaded area is salt. See Plate IX for the age of the correlated surfaces.
belt developed along the basinward limit of mid-Jurassic salt basin and involves minor amounts of shortening. The shortening of the fold belt does not correlate with the extensional growth faulting that formed landward of the fold belt before and after its formation. The Mississippi Fan Fold Belt appears to be related directly to the massive rise of active salt diapirs prior to the formation of large allochthonous salt structures. The relationship between the Mississippi Fan Fold Belt and the upslope allochthonous salt sheet and extensional growth faults can be summarized using seismic examples on Figures 7-9 and 10.
Note: Figure 7-9a is included in the pocket together with the plates and maps.
Note: Figure 7-9b is included in the pocket together with the plates and maps.
Note: Figure 7-10a is included in the pocket together with the plates and maps.
Note: Figure 7-10b is included in the pocket together with the plates and maps.
Chapter Eight

Models and Relationship Between Salt, Extensional and Contractional Tectonics on the Continental Slope

The geology of the slope of the northeastern Gulf of Mexico represents a linked system of salt, extensional and contractional tectonics. The understanding of salt tectonics in the Gulf of Mexico has evolved rapidly due to the improvements of seismic data and new analog experiments. In the following I would like to review some of the existing salt tectonic models and propose a new model for the evolution of autochthonous and allochthonous salt structures and their relationship with extensional and contractual systems. Again, the terminology used in the following discussion is summarized Appendix I. The subjects to be discussed are shown in a regional perspective in Table 8-1.

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Table 8-1 Major Meso-Cenozoic tectonic events in the northeastern Gulf of Mexico and the subjects discussed in Chapter Eight. The crustal types of the basement are adapted from Buffler (1989) and Salvador (1991b).
8.1. Models of the evolution of allochthonous salt sheets from previous study

A model for the evolution of allochthonous salt was proposed in a previous study (Wu et al, 1990b). As a summary, Figure 8-1 shows the typical deformation of salt on the platform and slope before mid-Cretaceous, as discussed in Chapter Four. After an extended period of stabilization of salt structures, following the mid-Cretaceous sea-level transgression (Chapter Five), allochthonous salt structures develop in response to the massive influx of sediments in the area. Figure 8-2 from our previous study shows a series of seismic examples representing each stage of the development of allochthonous salt. This model is further confirmed by the seismic data of this study. However, additional more advanced salt structures developed in the western part of the study area. The relationship between extension and salt movement was summarized in the reconstruction shown in Figure 8-3. We concluded that the extension on the master-down-to-the-basin growth fault is partly accommodated by the thinning and evacuation of the feeder stock and partly by the shortening in the fold belt. Also a system of extensional faults form and sole out on top of the allochthonous salt. Since the previous study was limited to the eastern part of the area, some of the observations were limited. A precise timing of the shortening of Mississippi Fan was not possible with my previous data base.

Thanks to more seismic data, detailed correlation and the detailed analysis of this study, I now come up with an improved model linking salt movement, extensional and contractional systems.

8.2. Models of salt diapirism

With improved seismic data and analog experiments, the formation of large allochthonous salt structures is better understood today. However, many questions remain about the process of salt diapirism, especially in the northeastern Gulf of Mexico where so
Figure 8-1a. Typical pre-mid-Cretaceous deformation on the shelf (after Wu, 1989). Salt rollers and the rotated and faulted overburden were common.

Figure 8-1b. Typical pre-mid-Cretaceous deformation on the slope (after Wu et al, 1990b). Pseudo-clinoforms and salt massifs formed.
Figure 8-2. Evolutionary stages of allochthonous salt as shown by line drawings of seismic examples (from Wu et al., 1990b). (a) Massive active salt diapirism; (b) Early salt spreading or allochthonous salt tongue; (c) Extended spreading or allochthonous salt sheet; (d) Detached allochthonous salt sheet.
Figure 8-3. Development of allochthonous salt and related master down-to-the-basin growth fault (Wu et al., 1990b). The extension on the master down-to-the-basin growth fault was largely accommodated by the thinning of salt feeder stock.
many tectonic events occurred during the massive upwelling of salt on the slope during the Middle-Late Miocene.

Since the basic work of Barton (1933) and Nettleton (1934), numerous models of salt diapirs formation have been proposed (e.g. Trusheim, 1960; Bishop, 1978; Vendeville and Jackson, 1992a) and modeled (e.g. Parker and McDowell, 1955; Sanford, 1959; Woidt, 1978; Talbot and Jackson, 1987; Schmeling, 1987; Jackson et al, 1988; Koyi, 1988; Vendeville, 1989; Römer and Neugebauer, 1991; Vendeville and Jackson, 1992a). Basically, diapir forming processes may be classified as active diapirism (Vendeville and Jackson, 1992a; also defined as upthrusting (Barton, 1933), upbuilding (Jackson et al, 1988) and active piercement (Jackson and Talbot, 1991)) and passive diapirism (Vendeville and Jackson, 1992a; also named downbuilding (Barton, 1933), and passive piercement (Jackson and Talbot, 1991)).

Most of the earlier models of salt deformation are based on fluid theory where overburden and salt are represented by viscous fluids. More recently, the experiments and models by Vendeville (1989) and Vendeville and Jackson (1992a) use a brittle layer representing overburden above a ductile layer representing salt.

As defined by Jackson and Talbot (1991), passive piercement is "syndepositional growth" of salt structures. The term is equivalent to the term "downbuilding". "The diapir increases relief by growing downward relative to the sedimentary surface (Figure 8-4b). Its base subsides, together with surrounding strata, as the basin fills with sediments. The diapir crest remains at or just below a thin roof that is continually thickened by sedimentation and thinned by erosion or extensional thinning". In this model, the roof overlying the salt dome is thin and further thinned by erosion or extensional thinning. Active piercement (upbuilding or active diapirism by others) is defined by Jackson and Talbot (1991) as "post-depositional diapiric growth (in the most extreme or ideal form) through prekinematic overburden (Figure 8-4a)". "Thus as the diapir increases in relief by
Figure 8-4. Schematic upbuilding (active diapirism) and downbuilding (passive diapirism) processes (Jackson and Talbot, 1991). Note that in upbuilding model, overburden must be displaced when the rising diapir pierced through the overburden. While in the downbuilding model the salt structure develops synsedimentarily. The salt diapir develops without displacing the overburden.
growing upward, its base remains at a constant depth below the sedimentary surface and its crest rises toward the sedimentary surface. More commonly, diapirs grow by a combination of the ideal end members of active and passive piercement because sediments accumulate while the diapir works its way to the surface." From my observation of the Gulf of Mexico, neither active nor passive piercement is exclusively responsible for the growth of all diapiric salt structures. One process may be dominant over the other under conditions that are related to volume of available salt (a function of salt thickness and drainage area), strength of overburden as a function of lithology (carbonates, sand or shale) and geometry of the overburden, tectonic settings (extension or contraction) and geographic position (shelf or slope).

Barton (1933) previously stated that in order to produce active piercement of the salt, the potential energy of salt under heavier sediments must be sufficient "(1) to overcome internal friction within the salt; (2) to overcome external friction between the salt and the surrounding sediments; (3) to do work in uplifting the salt against gravity; (4) to do work in uplifting the aureole of uplifted sediments against gravity; (5) to overcome friction within the sediments of that aureole". In addition, the upthrusting salt diapirs have (6) to break through the overburden. The ideal passive piercement according to Barton (1933) requires less energy than active diapirism since energy requirements (3), (4), (5) and (6) are diminished. The experiments of Vendeville and Jackson (1992a) show that coeval thin-skinned extension would help the piercement of salt through its overburden as shown in Figure 8-5. Vendeville and Jackson (1992b) conclude that diapir formation is easier with wide initial relief on the salt surface, thin roof sediments above the salt relief and a large thickness difference of loading. Extension therefore is a much more efficient trigger for diapirism than is differential loading.

The effects of active and passive diapirism on overburden are different. With ideal passive diapirism, the top of the diapir always remains near the sedimentary surface. Thus
Figure 8-5. The sequence of diapirism during thin-skinned extension (Vendeville and Jackson, 1992a). Note that the external extension is arbitrarily imposed in the development of salt diapir. The room for the rising diapir is accommodated by external extension.
the shape of the diapir also shapes the sedimentary basin (Figure 8-4b). There is little post-depositional deformation. Instead active diapirism is dominantly post-depositional. Thus with ideal active diapirism, the sediments above the diapir must be uplifted and/or removed for the salt diapir to rise up. In fluid models for example Figure 8-6 (Jackson et al, 1988), the overburden can deform unlimitedly to accommodate the upcoming salt diapir except at the boundary of the model. As shown in Figure 8-6, the overburden is thickened and deformed to give space to the upwelling salt diapir. In reality, however, the overburden cannot deform simply as a viscous fluid. There are several ways of removing overburden out of the way of a rising diapir. Erosion is one way as already suggested by Nettleton (1934) in Figure 8-7. The overburden above the diapir can also be removed by thin-skinned extension as suggested by Vendeville and Jackson (1992a) in Figure 8-5. Trusheim (1960) and again Seni and Jackson (1984) suggest that the pre-kinematic layer be flexed passively to give space for uprising diapir (Figure 8-8).

Parker and McDowell (1955) conducted a series of experiments to simulate the effects of the rising salt dome on overburden. Two of the many experiments that they conducted are of special interest to us. Figure 8-9 shows the fracture pattern produced by an asphalt dome which penetrated the mud surface. From this model we can see that when the dome actively pierced through the overburden, the overburden is moved out of the way by fracturing and upward bending. Obviously a lateral displacement component must exist within the fractured and uplifted overburden. Although not emphasized by the authors, we can see slightly folded mud around the edge of the model. This lateral displacement by piercement is dramatically shown by a "failed" model of Parker and McDowell (1955). Figure 8-10 shows their model with rigid plug piercing through a sand layer. The reverse faults in the sedimentary section clearly show the strain condition around a piercing dome. Although extreme, this experiment implies a strain condition that is similar to the fluid model in Figure 8-6. In reality, the lateral displacement of rising
Figure 8-6. Ductile deformation of viscous fluid overburden during diapirism (Jackson, Talbot, Cornelius, 1988). Note the severely deformed overburden especially interval C during the diapiric stage shown in Step 4. Lateral space required for the rising diapir is accommodated by the flexure and thickening of overburden.
Figure 8-7. Removal of overburden during diapirism by erosion (Nettleton, 1933). Note that the sediments are removed by erosion to make room for the rising diapir.

Figure 8-8. Deformation of flexible brittle overburden during active diapirism. (Seni and Jackson, 1984, modified from Trusheim, 1960). Note that the pre-kinematic interval above salt is highly deformed and uplifted to accommodate for the room needed for the rising diapir during diapiric stage D.
Figure 8-9. Fracture and fold patterns produced by asphalt dome which penetrated the mud surface (Parker and McDowell, 1955). Note that the overburden above the rising diapir is broken and uplifted. Minor compressional fold formed around the downdip end of the model.
Figure 8-10. Compressional deformation produced by the intrusion of a rigid plug (Parker and McDowell, 1955). Reverse faults occur in the section above the rising plug to accommodate the room needed by the rising plug.
Figure 8-11. Viscous fluid model showing the folded overburden in front of the rising salt structures (Model 5 of Talbot, 1992). Note the development of fold over the autochthonous salt in front of the salt sheet. Note also that the overburden 1 is highly thickened and deformed in the development of diapirs in Step R3.
diapirs is typically accommodated by flexure and faulting as shown by Figure 8-8 (Trusheim, 1960; Jackson and Seni, 1984). However, the response of the overburden to principally active diapirism is further complicated when large amounts of salt diapirs rise on the continental slope.

Talbot (1992) simulated the salt structures of the northern Gulf of Mexico using viscous fluid experiments. The contractional folds exist in the overburden basinward of the developing salt structures in his models (e.g. Figure 8-11). This shows that the contractional strains exist in the overburden during salt movements.

8.3. Models of salt deformation in the northeastern Gulf of Mexico

With the observations and analyses so far, I qualitatively conclude that gravity spreading and buoyancy driven salt flow due to differential loading and density inversion are the driving mechanisms for the formation of the salt structures on the continental slope of the northeastern Gulf of Mexico. For each stage of salt deformation, one mechanism is dominant. Before the mid-Cretaceous, the sedimentation was more landward to and near the mid-Cretaceous shelf margin where original salt was relatively thin. Salt deformed under differential loading and salt moved in the direction of lower pressure, i.e. the seaward end of the prograding sediment load. Thus the salt on the slope was not loaded by thick sediments, and buoyancy due to density inversion was not particularly effective. Salt deformation shifted progressively seaward as the depocenters prograded and salt was squeezed seaward. Bishop (1960) proposed a similar model in which salt is displaced in front of the prograding sediment loads. As discussed in Chapter Four, this period of seaward movements of salt was associated with a series of extensional faults above salt rollers below the mid-Cretaceous shelf. Faulting ceased as salt was evacuated, leaving behind a weld (Jackson and Cramez, 1989). In the offshore area, the movement of salt
caused turtle structures and pseudo-clinoforms and other salt related structures (Figure 8-1, Wu et al, 1990b). By mid-Cretaceous time, salt was mostly concentrated well beyond the mid-Cretaceous shelf margin in the form of autochthonous salt anticlines, domes and large salt massifs; only a few allochthonous salt pods occurred near the shelf margin. Most of the original salt bed below the mid-Cretaceous shelf is either eliminated, forming welds, or else thinned substantially. The Destin Dome area is the exception (Figure 1-5; MacGrae, 1990). The top of autochthonous salt was deformed as shown on Maps 3A and 3B.

The salt structures that formed before the mid-Cretaceous remained stable during the extended period of starved sedimentation of the mid-Cretaceous-mid-Oligocene (91.5-30 Ma). During this period, the near surface salt structures may have been modified by near-surface leaching. Biodegradation led to formation of less deformable cap rocks that may have formed on top of the near-sea-floor salt.

Since mid-Oligocene, the sedimentation rates (see Figure 2-11) increased rapidly in the slope area of the northeastern Gulf of Mexico. During the mid-Oligocene-Lower Miocene, previously formed autochthonous salt structures were reactivated by increased differential loading. The reactivation was expressed by the growth of salt diapirs and the associated formation of salt withdrawal basins. By the Middle Miocene, large amounts of sediments accumulated over the entire slope. The previously formed salt structures occurred at a typical depth below 2 seconds (varying from 1.5 to 4 seconds two way reflection time in most area) or nearly 3 km (converted using 3 km/second one way time) of mid-Oligocene-Middle Miocene sediment loads. The density inversion of salt occurred under thick differential sediment loads. Active diapirism driven by buoyancy force broke through the uneven overburden and facilitated the movement of salt from underneath the sediment load to near the sea floor.
Active diapirism is thought to be the dominant slope tectonic process during most of the late Early Miocene to the early Late Miocene. The top of salt was already deformed before the mid-Cretaceous as shown by the isopach of pre-mid-Cretaceous sediments overlying the salt structures as illustrated on Map 3. The Middle Miocene differential sediment loads associated with deltaic sedimentation increased the overburden significantly. All these factors lead to active diapirism (Vendeville and Jackson, 1992a). As a result of active diapirism, the lateral displacement of the pre-kinematic interval by rising salt diapir was in part accommodated by the flexure of the overburden. How much of the lateral displacement the flexure can be accommodated and in what manner depend on the flexibility of the overburden. Viscous fluid modeling e.g. Figure 8-6 from Jackson et al (1988), assumes that the overburden can deform in almost any way to accommodate the rising less dense diapir.

In reality, however, the overburden may not be as flexible as a viscous fluid. In that case the lateral displacement of the large active diapirs cannot adequately be accommodated by ductile deformation of overburden. Consequently I propose that lateral displacement not accommodated is transmitted laterally downslope using autochthonous salt as decoupling level. Before the massive salt diapirism during the Middle Miocene, the top of the autochthonous salt was deformed and inclined basinward as suggested indirectly by the isopach Maps 3A and 3B and the structure map on mid-Oligocene (30 Ma) in Map 10. Figure 8-13 sketches the effect of salt diapirism on the overburden on the continental slope of the northeastern Gulf of Mexico during the Middle Miocene. The gravity component parallel to slope forced the lateral displacement associated with the diapir to be transmitted asymmetrically in the downslope direction. This lateral displacement ceased when active diapirs pierced though overburden and began to spread downslope as sheets within the shallow sediments.
After the diapirc stage, large amounts of salt were transported by buoyancy to near the sea floor to form allochthonous salt structures. As soon as salt reached shallow levels, the density inversion was equilibrated with the shallow surrounding sediments. Excessive amounts of salt transported from the diapirc feeder stocks began to spread gravitationally downslope within the near-sea floor sediments. This spreading process was accelerated by continued differential sedimentation on top of the allochthonous salt. Thus the allochthonous salt is further deformed by differential loading and gravity spreading. Downslope spreading of allochthonous salt was very rapid and continued throughout its emplacement. The allochthonous salt further moved basinward under prograding sediment loads. The base of the allochthonous salt sheet truncates the sediments below (e.g. Figure 6-2). Also, the base of the allochthonous salt sheet steps upward dynamically as episodic loading occurs on top of the salt sheet (e.g. Figure 8-2c, Wu et al, 1990). The leading edge of the allochthonous salt forcefully deforms the sediments in front and above and is responsible for the Sigsbee Escarpment on the lower slope of the northern Gulf of Mexico (e.g. Figure 7-6, Map 1 and Figure 1-1).

8.4. Relationship with salt movements and extensional systems

Looking at the Mississippi Fan area in isolation, I cannot explain the formation of the fold belt. Before discussing the possible models for the formation of the fold belt, I need to discuss the timing and space relationship between Mississippi Fan Fold Belt and the development of landward extensional systems and allochthonous salt.

Map 10 shows the time-structure of the 30 Ma sequence boundary. This surface is an important reference surface which is related to the structures of the Mississippi Fan Fold Belt. The map shows that the deformation is restricted seaward by the southern limit of the mid-Jurassic salt (Figure 8-12). Immediately to the north are the extensive
Figure 8-12. Effect of a frictional boundary on shortening. Shortening in the Mississippi Fan Fold Belt is focused near the basinward limit of the mid-Jurassic salt.
Figure 8-13. A schematic model for the initiation and cessation of shortening in the Mississippi Fan Fold Belt by salt movements. (a) Before Mississippi Fan Fold Belt was formed, there was no major salt diapirism in the upslope direction. (b) During massive salt diapirism, the lateral displacement of the overburden caused by the rising diapir was transmitted and accumulated near the basinward limit of the mid-Jurassic salt. The Mississippi Fan Fold Belt was thus formed. (c) The shortening in the fold belt ceased when salt pierced through the overburden and began to spread on within slope sediments near sea floor. Large primary withdrawal basins formed landward to the allochthonous salt sheet.
allochthonous salt structures and associated feeder systems which laterally displaced the sediments above the autochthonous salt (Figure 8-13). Some of the feeder stocks are mappable on seismic profiles but many of them are unmappable due to limited subsalt imagery by conventional reflection seismology. However, the evolution of allochthonous salt from autochthonous salt has now been widely accepted (e.g. Humphris, 1978; Bally, 1981; Buffler, 1983; Jackson et al 1988; Worrall and Snelson, 1989; West, 1990; Wu et al, 1990b). Thus, a feeder system within the sediment column between autochthonous and allochthonous salt should exist under each isolated allochthonous salt body seen on Map 10. However the actual diameter and shape of each feeder is difficult to quantify with present 2-D seismic data.

On Map 10, we can see that relatively broad withdrawal basins to the north involve very limited extensional faulting relative to the well-developed contractual faulting in the Mississippi Fan Fold Belt. Map 16 shows both normal and reverse faults on the 30 Ma surface. However, we can see that the normal faults are sparse. Most of the normal faults show minor extension except for one occurring in the Mississippi Canyon area shown on regional profiles D9, D10 and D11 and Figure 7-10. This fault was described as a "down-to-the-basin master growth fault" in the previous study (Figure 8-3, Wu et al, 1990b). The relationship of this fault with the formation of allochthonous salt and the Mississippi Fan Fold Belt was analyzed by Wu et al (1990) and Moretti et al (1990). It was concluded that the large extension on this growth fault is accommodated partly by the thinning of an originally thick feeder stock and partly by the shortening in the Mississippi Fan Fold Belt. As we look at Map 10 and Map 16, I find that there is only one large down-to-the-basin master growth fault in the entire continental slope of the study area. Near the down-to-the-basin master fault, the extension is very much more than the shortening in the downdip fold belt, while in most of other places, the shortening cannot be accounted for by the extension on the limited number of normal faults of the study area. This observation leads
to a question of "What is or are the real causes for the shortening of the Mississippi Fan Fold Belt aside from the updip extension expressed by the normal faults?".

Map 17 shows the faults that cut the 5.5 Ma surface. We can see that although the shortening of the Mississippi Fan Fold Belt ended by 5.5 Ma or earlier, the extension continues. This fact suggests that the shortening in the Mississippi Fan Fold Belt was formed by a mechanism other than the extension of the normal faults. Most of the normal faults on the 5.5 Ma are distributed between the allochthonous salt structures. And their distribution shows that they are mostly related to the withdrawal of the autochthonous salt due to transfer into the allochthonous salt. Many of the faults diminish at depth as shown on regional profiles D1-D20 on Plates I-IV.

Map 18 shows the fault system that cuts the 1.9 Ma surface. We can see that extensive normal faults mostly develop on top of the allochthonous salt. These extensional faults do not develop a corresponding contractional system. There are only a few cases of local contractional folds and reverse faults developed about the 1.9 Ma surface above the allochthonous salt. In conclusion the Mississippi Fan Fold Belt has been inactive since Late Miocene and was not activated by later increased sediment loading (Maps 14 and 15, Figure 2-11) and extensive normal faulting in the updip areas (Maps 17 and 18).

The contradictory relationship between later extension on normal faults and earlier shortening in the Mississippi Fan Fold Belt revealed on Map 10, Map 16, Map 17 and Map 18 suggests that the extension and the shortening in the Mississippi Fan Fold Belt are not directly related. The deformation and movement of both autochthonous and allochthonous salt under differential sediment loading may provide for an explanation of the extension by normal faulting and the shortening in the Mississippi Fan Fold Belt.
8.5. Mechanism of initiation and cessation of shortening in the Mississippi Fan Fold Belt

The Mississippi Fan Fold Belt is formed along the southern edge of the mid-Jurassic salt basin as shown on Map 10. This suggests that the fold belt coincides with a mechanical boundary that separates the low shear strength salt substrate from a non-slip oceanic basement-sediment contact. The extensional strains from the updip area transmitted to and accumulated along this mechanical boundary and formed the Mississippi Fan Fold Belt. The effect of the frictional boundary is sketched on Figure 8-12. The presence of a mechanical boundary effectively limits the total width of the fold distribution. Thus, the well focused shortening due to the mechanical boundary of the decoupling surface. Colletta et al (1991) conducted experiments with a designed frictional boundary. They also concluded that the presence of frictional boundary affects the distribution and the geometry of the thrust faults.

8.5.1 Time and space relationship between extension and contraction

As I discussed in the previous chapter, Map 10 and Map 16 show that there is either too much extension near the only down-to-the-basin master growth fault relative to the shortening in the Mississippi Fan Fold Belt, or else in most of the other places there are too few normal faults with too little extension to explain the systematic shortening of the Mississippi Fan Fold Belt. Also on Maps 17 and 18, we see later well-developed extensional systems with no corresponding contractional system. As documented on Map 10, 16, 17 and 18 I can conclude that 1) the Mississippi Fan Fold Belt is not likely to be a consequence of the limited extensional normal faulting upslope; and 2) the extension on normal faults may not have to be accommodated by the contraction as required by the gravity gliding model (e.g. Mandl, and Crans, 1981). Consequently I would like to explore 1) what process accommodated the widespread extension associated with the normal
faults before and after the formation of the Mississippi Fan Fold Belt; 2) what process initiated and terminated the shortening of the Mississippi Fan Fold Belt.

Early extensional normal faulting began not too long after the deposition of the mid-Jurassic Louann salt. As I discussed in Chapters Four, Five and Six, peripheral faults developed near the updip limit of the mid-Jurassic salt basin, faulted and rotated blocks related to salt rollers developed under the mid-Cretaceous shelf, and other normal faults developed on top of the autochthonous salt before the formation of the Mississippi Fan Fold Belt. The extension along these normal faults appears to be accommodated by the deformation and basinward flow of the autochthonous salt. As I discussed in Chapter Four, before the mid-Cretaceous, most of the autochthonous salt was deformed and covered by unevenly distributed sediments. There is no convincing evidence that regional contractional systems developed in response to any of the earlier extensional fault system mentioned above.

The Mississippi Fan Fold Belt was fully developed by Late Miocene. However extensional systems continue to develop until today. We know from Map 10 and Map 16 that many extensional faults formed after the cessation of the Mississippi Fan Fold Belt. Few if any of them displace the deeper section (e.g. 30 Ma). The post-fold belt normal faults do not detach at the autochthonous salt level which is the main decoupling level for the fold belt. This suggests that although many normal faults form after the cessation of the fold belt, they are not related to the shortening across the Mississippi Fan Fold Belt simply because these systems mostly developed later and use different decoupling levels and mechanisms. What then accommodated the extension that decoupled at shallow depths? First, we need to look at those faults that cut the 5.5 Ma surface (Map 17). Except for the normal faults already shown on Map 10, most of the normal faults on Map 17 are shallow faults. Regional profiles D1-D20 on Plates I-IV reveal clearly that these shallow faults with their limited extension are mostly tension faults caused by the
formation of the underlying turtle structures. I conclude that the extension on most of the normal faults on 5.5 Ma is caused and accommodated by the withdrawal of the deep autochthonous salt that fed the allochthonous salt.

Faults that cut the 1.9 Ma surface shown on Map 18 are all normal faults and mostly located on top of the allochthonous salt. Some faults that are not on top of the allochthonous salt (see D1-D20) are the extension of tensional faults that cut the 5.5 Ma surface. Faults above the allochthonous salt (see D1-D35 and S1-S8) are closely related to the deformation and movement of allochthonous salt around secondary and tertiary withdrawal basins. Many of the supra-allochthonous-salt normal faults show wide extension, but they clearly do not contribute to the shortening of the Mississippi Fan Fold Belt because they are higher and not connected with the basal décollement of the fold belt.

Knowing that pre-and post-Mississippi Fan Fold Belt tectonics did not contribute to the shortening of the fold belt, we now can focus on the Middle-Late Miocene interval when the Mississippi Fan Fold Belt was active. Some extensional faults active during this period may be related to the shortening in the fold belt such as the extension in the down-to-the-basin master fault system discussed earlier. From Map 16 we know that this kind of fault is an exception. Overall, the coeval extension by the normal faults is clearly not adequate to form the fold belt.

8.5.2. Models for the development of the Mississippi Fan Fold Belt

There are several possible sources of extension north of the Mississippi Fan Fold Belt that may initiate the shortening in the fold belt.

A first option is that Middle-Late Miocene extensional growth faults located to the north are soling out in the autochthonous salt such as the unique down-to-the-basin-growth master fault observed earlier (Wu et al, 1990b). The northern limit of my data does not permit to say whether deeply decoupled Middle-Late Miocene extensional faults occur
farther north. Most of the available industrial seismic data in the areas north of this study do not penetrate deep enough. Typically the available data are just 6-8 seconds (two way time) deep. Ten to eleven seconds (two way time) data would be required to see the base of autochthonous salt. Be this as it may, we still would need to find a mechanism to explain the Late Miocene cessation of folding.

I prefer a second option that relates the shortening in the fold belt with the massive rise of salt diapirs to the north of the fold belt on the continental slope. As discussed in Chapter Six large amounts of salt formed rising diapirs during the Middle-Late Miocene, thus the diapiric stage is contemporaneous with the development of the fold belt (Table 8-1). The cessation of the folding followed later with the early spreading of allochthonous salt. Reconstructions suggest that extensive diapiric salt structures formed during Middle-Late Miocene time (see Moretti et al, 1990). These diapiric structures laterally displaced sediments downslope using the autochthonous salt as the decoupling level up to the basinward edge of the mid-Jurassic salt basin. Thus, the Mississippi Fan Fold Belt responded to the massive rise of diapirs. The lateral displacement causing the Mississippi Fan Fold Belt ceased when the salt diapirs reached shallow depths and began to spread within the younger sediments during the Late Miocene.

Figure 8-13 sketches the proposed model for the initiation and cessation of the shortening in the fold belt. Figure 8-13a illustrates the situation just before the massive rise of salt diapirs. This phase corresponds to the early Middle Miocene in the western part and to about middle Middle Miocene in the eastern part of my area. The key elements are the slope setting, the frictional boundary at the basinward limit of salt, and the autochthonous salt massifs. The salt massif later developed into salt diapirs driven by buoyancy under rapidly deposited sediment loads as shown in Figure 8-13b. The rising salt diapir displaced the overlying sediments. Strains were accumulated near the frictional boundary between salt and salt-free area. Soon after the allochthonous salt began to
spread near the sea floor, the lateral displacement and shortening due to salt diapirism ceased, as shown in Figure 8-13c. As a result, the shortening in the fold belt stopped while new extensional salt withdrawal basins (with or without associated fault systems) developed when massive autochthonous salt moved away to form large allochthonous salt. In conclusion, the source of shortening in the Mississippi Fan Fold Belt is the lateral downslope sediment displacement caused by the massive rise of salt diapirs in the updip areas. The location of the fold belt is constrained by the basinward edge of the mid-Jurassic salt. This explains an apparently unbalanced situation between sparsely distributed coeval extensional faults and systematic occurrence of the fold belt (Map 10).

8.6. Summary

With each stage of salt movement, specific types of structures formed in the overlying sediments. During the seaward movement of salt before mid-Cretaceous (150.5-91.5 Ma), a peripheral fault system, salt rollers, turtle structures and pseudo-clinoforms were formed under the mid-Cretaceous platform and slope. Salt structures stabilized during the mid-Cretaceous to mid-Oligocene (91.5-30 Ma) period of starved sedimentation.

During the mid-Oligocene to Early Miocene (30-15.5 Ma) reactivation period, local withdrawal basins and associated extensional faults developed. During the Middle to Late Miocene (15.5-5.5 Ma) diapiric stage, the Mississippi Fan Fold Belt formed along the southern edge of the mid-Jurassic salt basin, and the withdrawal basins and related growth faults continued to form. The Mississippi Fan Fold Belt ceased to grow when the spreading of the allochthonous salt began during the Late Miocene, even though the sedimentation increased greatly since the development of the Pliocene Mississippi Delta and Fan. Extensive primary, secondary and tertiary withdrawal basins and associated
growth faults formed as salt deformed under differential sediment loading. The rising allochthonous salt formed a large sediment trap which prevented large volumes of sediment to be transported to the deep Gulf of Mexico. Primary to quintic weld systems of various scales formed where salt was evacuated from the mother salt to produce feeder systems and primary and secondary allochthonous salt tongues and sheets.

I conclude that massive salt movements under differential sediment loading on the continental slope control the development of both regional extensional and contractional systems. Extensional systems of various ages and extent are the consequences of salt withdrawal during the Late Jurassic to present. The Mississippi Fan Fold Belt was formed by the massive diapiric rise of salt since the early Middle Miocene (15.5 Ma-13.8 Ma) and ceased when allochthonous salt began to spread near the sea floor by the end of Late Miocene (5.5 Ma).
Chapter Nine

Sub-Allochthonous Salt Structures

In the northeastern Gulf of Mexico, a large part of the continental slope is covered by allochthonous salt structures except for the east corner of the area (see Map 6). Thus, toward the eastern end of our area, we see seismic reflections well down to the base of autochthonous salt because the allochthonous salt is absent. In rare cases, the sub-allochthonous structures are seismically mappable. On the other hand, in most cases the structures underneath the allochthonous salt are not well imaged by seismic profiles. We may combine whatever data we have with the tectonic model established in this study to speculate about the possible structural styles below the allochthonous salt.

9.1. Salt structures

Most of the salt on the continental slope of the study area is presently distributed as allochthonous salt (regional seismic profiles D1-D35 and S1-S9). Under the load of the rapidly deposited Neogene-Present sediments, the autochthonous salt bed was thinned or eliminated to form primary welds. Some of the autochthonous salt remains in the Mississippi Fan Fold Belt. A salt feeder was connected with each individual allochthonous salt structure as discussed in Chapter Six. The remnants of salt feeders are not well imaged by seismic data and difficult to delineate. Occasionally, the feeder system may be wide as shown on D4-D6, D8-D14, D17-D19 and the reconstruction on Figure 8-3. The feeder systems may (e.g. D9-D11) or may not (e.g. D17-D19) be squeezed out by sediment loading and accommodation to updip extension.

The salt structures below the allochthonous salt involve either thin salt or welds. Regional profiles D26, D27, D31-D35 and Figure 6-7 show very thin primary
Figure 9-1. Index map for seismic examples in Chapter Nine.
allochthonous salt under the secondary allochthonous salt. We also see some of the feeder systems that connect the primary with secondary allochthonous salt analogous to the feeder system between autochthonous salt and primary allochthonous salt.

9.2. Extensional systems

Most of the allochthonous salt occur in an extensional domain. Extensional structures formed before, during and after the emplacement of the allochthonous salt exist. Map 10 shows the extent of both extensional and contractional domains in the study area. From this map, it can be roughly predicted which or part of which allochthonous salt are underlain by extensional structures. Generally, anywhere to the north of the Mississippi Fan Fold Belt, extensional structures prevail above and under the allochthonous salt.

Extensional structures are best observed in the area not covered by allochthonous salt. Important structures are normal fault systems and turtle structures and pseudoclines associated with primary salt withdrawal. These structures are likely to underlie allochthonous salt that emplaced since the Middle Miocene when the autochthonous salt related extensional systems developed. Figure 9-2 shows one of the best imaged sub-allochthonous salt structures of the study area. Still, the details of the structure are not resolved. A near by seismic line shows in detail an extensional system not overlain by allochthonous salt (Figure 9-3). Structures not covered by allochthonous salt give us some hint about what to expect underneath the allochthonous salt. The extensional structures seen on Map 10 may well continue underneath the allochthonous salt. Many structures such as those shown by Figure 9-4 may occur underneath the allochthonous salt. These structures are interesting for deep hydrocarbon exploration. Most of them are related to the withdrawal of mother salt.
Figure 9-2a. An uninterpreted NW - SE seismic example of subsalt structure. See Figure 9-1 for location of seismic line.
Figure 9-2b. An interpreted NW - SE seismic example of subsalt structure across well Mississippi Canyon 211 Exxon #1. See Figure 9-1 for location of seismic line and Figure 2-2 for well location. The subsalt reflections are well imaged. Note that the leading edge of the salt sheet uplifted the overburden and formed a sea floor high. The shaded area is salt. See Plate IX for the age of the correlated surfaces.
Figure 9-3a. An uninterpreted NW-SE seismic example of structure related to salt withdrawal. See Figure 9-1 for location of seismic line.
Figure 9-3b. An interpreted NW - SE seismic example of structure related to salt withdrawal. See Figure 9-1 for location of seismic line. The shaded area is salt. See Plate IX for the age of the correlated surfaces.
Figure 9-4a. An uninterpreted NW-SE seismic example of salt-withdrawal related structure across well Mississippi Canyon 730 Shell #1. See Figure 9-1 for location of seismic line.
Figure 9-4b. An interpreted NW-SE seismic example of salt-withdrawal related structure across well Mississippi Canyon 730 Shell #1. See Figure 9-1 for location of seismic line and Figure 2-2 for well location. The shaded area is salt. See Plate IX for the age of the correlated surfaces.
Structures underneath the secondary allochthonous salt are almost entirely extensional and formed over the primary allochthonous salt. Most of these structures are simple highs and lows with little significant faulting (see regional profiles D26-D27, D31-D35 and S3-S4). They are covered and cut by the salt feeder stock and the spreading sheet.

9.3. Contractional systems

The contractional Mississippi Fan Fold Belt is in part underlying the leading edge of the southward advancing allochthonous salt. Map 10 shows the changes of width of the Mississippi Fan Fold Belt that is not covered by the allochthonous salt. How far the fold belt extends under the allochthonous salt is open to question. At least some of compressional structures are present below the allochthonous salt. Seismic examples Figures 9-5 and 9-6 show such contractional systems that are partly covered by allochthonous salt sheet. As discussed in Chapter Seven, the spreading of the allochthonous salt began after the Mississippi Fan Fold Belt ceased to develop. Whether the contractional structures are covered or not by the allochthonous salt, should not influence their styles of deformation. The sub-allochthonous salt part of the Mississippi Fan Fold Belt is not likely to be much wider than the widest part of the uncovered fold belt. This point is illustrated by the regional profiles on Plates VI and V.

9.4. Summary

Extensive allochthonous salt covers a great number of extensional and contractional structures on the continental slope of the northeastern Gulf of Mexico. Most of these structures are similar to those not hidden underneath the allochthonous salt sheets. Some sub-allochthonous salt structures may be good hydrocarbon exploration targets. To map
Figure 9-3a. An uninterpreted NW - SE seismic example of subsalt fold and reverse fault. See Figure 9-1 for location of seismic line.
Figure 9-5b. An interpreted NW-SE seismic example of subsalt fold and reverse fault. See Figure 9-1 for location of seismic line. The shaded area is salt. See Plate IX for age of the correlated surfaces.
Figure 9-6a. An uninterpreted NE-SW seismic example of subsalt fold and reverse fault perpendicular to Figure 9-4a. See Figure 9-1 for location of seismic line.
Figure 9-6b. An interpreted NE-SW seismic example of subsalt fold and reverse fault perpendicular to Figure 9-4b. See Figure 9-1 for location of seismic line. The shaded area is salt. See Plate IX for the age of the correlated surfaces.
the subsalt structures adequately, the seismic imaging techniques need to be greatly improved.
Chapter Ten

Supra-Allochthonous-Salt Structures

Widespread allochthonous salt separates structures above from structures below salt. Structures formed on top of the allochthonous salt often are decoupled from that top. And, of course, the base of the allochthonous salt itself is a decoupling surface. The allochthonous salt thrusts over the younger sediments below and in front as it spreads downslope. Thick allochthonous salt can accommodate large amounts of overlying sediments. Thus many individual supra-allochthonous-salt basins formed under the load of post-Miocene deltaic deposits (see Map 8). For the context of supra-allochthonous-salt structures discussed in this chapter, see Table 10-1.

Table 10-1 Major Meso-Cenozoic tectonic events in the northeastern Gulf of Mexico and the subjects discussed in Chapter Ten. The crustal types of the basement are adapted from Buffler (1989) and Salvador (1991b).
10.1. Secondary allochthonous salt structures

The time-structure map of the top of allochthonous salt Map 7 shows the deformed top. More recent allochthonous salt in the east is less deformed than the older allochthonous salt to the west. Structural relief is in excess of 5 seconds (two way time). In the Green Canyon area, secondary allochthonous salt structures (see Appendix I for definition) developed over highly deformed primary allochthonous salt sheets. As shown on Map 6, most of the allochthonous salt sheets occur in the middle and lower slope. The allochthonous salt of the upper slope is thinned or evacuated to form tertiary welds. The secondary allochthonous salt structures controlled the sediment distribution on the slope since the late Middle Miocene. Much of the allochthonous salt is squeezed in front of a prograding sedimentary wedge (e.g. Map 6 and Map 8). No regional extensional faulting precedes the salt diapirism that forms the secondary allochthonous salt. The differential supra-allochthonous-salt sediments on slope is the cause of the allochthonous salt deformation.

10.2. Extensional systems

The fault map of the 1.9 Ma surface shows the extensional systems over the allochthonous salt. Large withdrawal basins occur with or without associated growth faults. Extensional growth faults form over the allochthonous salt as a consequence of salt withdrawal as shown by some seismic examples. Figure 10-2 shows the leading edge of a large allochthonous salt sheet. The allochthonous salt in the northern end of this example is evacuated to form a weld under a thick sediment load. The salt is concentrated in the basinward end of the allochthonous salt sheet. As sediments prograde, salt is squeezed farther basinward to deform the sea floor above the leading edge of the salt sheet and new depocenters develop over the salt sheet. Most of the faults are very recent and extension is
Figure 10-1. Index map for seismic examples in Chapter Ten.
Note: Figure 10-2a is included in the pocket together with the plates and maps.
Note: Figure 10-2b is included in the pocket together with the plates and maps.
accommodated by the spreading allochthonous salt. The spreading salt, in turn, deforms
the overlying sediments and sea floor to make space for additional sediments. Thus for
most supra-allochthonous-salt systems, extensional structures prevail. Contractional
structures in the sediments are the rare exception and will be discussed in the next section.
Map 18. shows extensional faults as a consequence of salt withdrawal rather than the
cause of salt movements. As depocenters continue to develop, salt is withdrawn and the
extension along growth faults increases (see seismic example Figure 10-3). Some parts of
the allochthonous salt are thinned and tertiary welds form under the supra-allochthonous-
salt depocenters. With further loading, the tertiary welds will further develop. Another
good example of thinned allochthonous salt with an overlying extensional system is shown
on Figure 10-4. A seismic line perpendicular to Figure 10-4 is shown in Figure 10-5 where
large extension on the growth faults is accommodated by salt spreading and salt
withdrawal. Note that no major salt structures develop along growth faults.

Large tertiary welds or thinned allochthonous salt systems occur in the Green
Canyon area as shown on Map 6. In many places, however, the thinned allochthonous salt
is not easily recognizable. The shallow growth faults on the slope are usually related to the
allochthonous salt or tertiary weld. Figure 10-6 illustrates such a large extensional growth
fault on top of a thinned primary allochthonous salt and its tertiary weld. Figure 10-6 also
shows thinned allochthonous salt with some extension.

10.3. Contractional systems

Most of the supra-allochthonous-salt extension is accommodated by salt
movements rather than by contractional faults. Occasionally, however, I find some
compressional structures above the allochthonous salt. Take the 1.9 Ma surface as an
Note: Figure 10-3a is included in the pocket together with the plates and maps.
Note: Figure 10-3b is included in the pocket together with the plates and maps.
Note: Figure 10-4a is included in the pocket together with the plates and maps.
Note: Figure 10-4b is included in the pocket together with the plates and maps.
Figure 10-5a. An uninterpreted NW - SE seismic example of tertiary welds perpendicular to Figure 10-3a. See Figure 10-1 for location of seismic line.
Figure 10-5b. An interpreted NE-SW seismic example of tertiary welds and secondary withdrawal basin perpendicular to Figure 10-3b. See Figure 10-1 for location of seismic line. The shaded area is salt. See Figure 10-1 for location of seismic line. See Figure 10-1 for location of seismic line.
Note: Figure 10-6a is included in the pocket together with the plates and maps.
Note: Figure 10-6b is included in the pocket together with the plates and maps.
example. On Map 18, there are a few contractional faults near the leading edge of the allochthonous salt. Most of these faults are local and extend only over 2-3 mi.

Figure 10-7 shows a deformed allochthonous salt sheet and its overlying extensional and contractional structures. The top of the salt sheet dips to the south. The allochthonous salt itself is deformed. The leading edge of the salt sheet is thinned, and a tertiary weld forms below thick overburden. The tertiary weld is locally restricted as seen on the perpendicularly seismic line across the weld (Figure 10-8). The thinned salt and its overburden reduce the mobility of the salt sheet near the leading edge. Behind the weld and the thinned leading edge, the salt sheet is thicker and hence more mobile. Thus between the downslope weld and thicker salt upslope there exists a frictional boundary that is mechanically comparable to the basinward edge of the mid-Jurassic salt of the Mississippi Fan Fold Belt. Thus, the compressional faults formed on top of the thicker part of the salt sheet and the fold formed over the thinned leading edge of the salt sheet.

Upslope from the reverse fault are north and south dipping growth faults. Is the extension on these upslope growth faults accommodated by the shortening in the fold? The extension on the basinward dipping normal fault started after P2. However, there are two phases of shortening for the reverse fault. A first shortening event happened before PL12. Upslope, the coeval PL11-2 interval shows convergence against the salt sheet. This shows that the first phase of shortening is due to the rising of salt diapirs. The fold was dormant since PL12 and was reactivated after P3 during the second phase of shortening. Extensional faulting on the seaward-dipping fault occurred since P2. Thus it doesn't correlate with the second shortening phase. A major landward dipping counter-regional growth fault north of the fold developed during the second phase of folding. Therefore growth faulting coincides with the lateral withdrawal of the salt as shown in Figure 10-8. The reverse fault and the fold ceased to grow but the updip counter-regional fault remains active. I conclude that the first phase of folding is directly related to salt growth to the
Note: Figure 10-7a is included in the pocket together with the plates and maps.
Note: Figure 10-7b is included in the pocket together with the plates and maps.
Note: Figure 10-8a is included in the pocket together with the plates and maps.
Note: Figure 10-8b is included in the pocket together with the plates and maps.
north. The second phase of folding was not caused by either seaward or else landward
dipping growth faults. Both phases of compression are related the movement of the
allochthonous salt sheet.

Huber (1989) documented a supra-allochthonous-salt thrust system of the Ewing
Bank area as shown in Figure 10-9. The thrust faults are presumably over a tertiary weld
and in front of a seaward moving salt sheet. Lateral salt deformation in this case initiated
the thrusting.

Cook and D'Onfro (1991) documented a supra-allochthonous-salt thrust system in
Green Canyon areas of the northeastern Gulf of Mexico. Cook and D'Onfro (1991) made
a detailed analysis on the development of the thrust fault. Their reconstruction of the
thrust fault is shown on Figure 10-10. We can see that during the stage of overthrusting
shown on Figure 10-10c, the diapir pierced through the over burden and lifted the top
surface with dips exceeding 16°, which is the critical stability dip for the upper surface
(Cook and D'Onfro, 1991). Based on slope stability modeling they conclude that "the
Jolliet Field thrust fault formed as the toe of a major gravity slide which was triggered by
salt movement on the flank of an inter domal basin". The thrusting ceased during the late
Illinoian because a) the rate of sedimentation exceeded the growth rate of salt and the dip
of the slope was reduced by sedimentation; b) increased sediment overburden increased
the shear strength on the thrust fault (Cook and D'Onfro, 1991). Figure 10-10D doesn't
support point a). It seems that the salt growth was balanced by sedimentation. Thus the
thrust fault was caused by active diapirism in Figure 10-10C which displaced neighboring
sediments downslope. Thrusting stopped when the salt structure to the north continued to
grow passively without further lateral displacement. The thrust faulting and the withdrawal
of salt from under the thrust significantly reduced the dip of the sediment surface.
Figure 10-9. Seismic example of reverse faults formed near a tertiary weld by advancing allochthonous salt sheet (after Huber, 1989).
Figure 10-10. Reconstruction of Jollet Field thrust fault (from Cook and D’Onfro, 1991). Note that reverse fault occurred in C when the updip salt diapir developed.
10.4. Summary

Supra-allochthonous salt structures are separated from the sub-allochthonous salt structures by the allochthonous salt itself. The allochthonous salt is deformed in response to the amount of overburden. Salt ridges, diapirs, secondary allochthonous salt structures, thinned salt, and tertiary welds all occur over the allochthonous salt level. Most of the allochthonous salt is being squeezed in front of a prograding deltaic sediment wedge. The allochthonous salt is still being deformed driven by gravity spreading under differential loading on the slope and by buoyancy forces in case of density inversion under thick differential overburden. The active leading portion of the allochthonous salt deforms the sea floor. Supra-allochthonous salt sediments also deform as the allochthonous salt deforms. Large extensional growth faults are accommodated by the spreading and withdrawal of the allochthonous salt. On rare occasions, local reverse faults and folds exist above the allochthonous salt when diapirism on the slope is associated with proper frictional boundary conditions.
Chapter Eleven

Submarine Erosion

Erosion on various scales is observed on the slope of the northeastern Gulf Mexico. Without entering into discussion concerning deep-water erosional mechanisms, I limit myself to showing some seismic examples of submarine erosion.

11.1. Incision of submarine canyons

The most recent submarine canyon in the area is the Mississippi Canyon. Similar canyon systems are common during the Plio-Pleistocene development of the Mississippi Fan (e.g. Weimer, 1989; Coleman et al, 1991). One seismic example of submarine canyon from the area is shown in Figure 11-2.

11.2. Erosion related to turbid flow

Great amounts of erosion at the base of fan lobes are observed within the Plio-Pleistocene Mississippi Fan (Weimer, 1989; Coleman et al, 1991). This kind of erosion is commonly associated with the turbid flows during the development of the Pleistocene Mississippi Fan. Some examples are shown in Figure 3-5.

11.3. Erosion related to non-deposition due to starved sedimentation

Additional regional submarine erosion occurred often in association with non-deposition and condensed sedimentation. The most pronounced period of starved sedimentation is the mid-Cretaceous (91.5 Ma) to mid-Oligocene (30 Ma) interval following the Turonian maximum flooding and the associated lack of sediment supply in
Figure 11-1. Index map for seismic examples in Chapter Eleven.
Figure 11-2a. An uninterpreted NE-SW seismic example of a submarine canyon. See Figure 11-1 for location of seismic line.
Figure 11-2b. An interpreted NE-SW seismic example of submarine canyon. See Figure 11-1 for location of seismic line. Note that the canyon eroded the sediments below. The correlated stratigraphic surfaces UM-Upper Miocene (5.5 Ma) and PLI-Pliocene (1.9 Ma). The shaded area is salt.
the slope area (Figures 2-10, 2-11). Like on the present Florida Escarpment (e.g. regional profiles S4-S6), the structures below 91.5 Ma surface were eroded during about 60 million years of overall starved sedimentation. We can see from the regional profiles S1-S9, and D1-D18 that in many places the 91.5 Ma surface is an angular unconformity. I think the erosion associated with 91.5 Ma is due to ocean currents.

11.4. Erosion of the Mississippi Fan Fold Belt and the Sigsbee Escarpment

Spectacular erosion is also observed along the present Sigsbee Escarpment above the leading edge of the allochthonous salt sheet. As shown by seismic example Figure 11-3, the Sigsbee Escarpment is being eroded at about 2,000 meters of water depth. The scarp is eroded due to ocean currents. On the regional profiles (e.g. D23-D29 on Plate VI), we can also see that many sea floor highs are either bypassed by sediments or else actively eroded.

Widespread regional erosion occurs in the Mississippi Fan Fold Belt. As shown on Figures 7-2, 7-5, 7-6, Figure 11-3 and on the regional profiles S7 and S8, the top of the folds are eroded away. There are no obvious channels, canyons, or overlying fan systems related to these erosional surfaces. Although the ages of the erosional surfaces appear to differ from west to east, they all were formed by similar mechanism. The erosional surface is the Middle Miocene in the west and Upper Miocene in the east. Map 13 (10.5-5.5 Ma time-thickness map) shows that during the Late Miocene, most of the sediments were deposited in salt withdrawal basins to the north of the allochthonous salt. The sediments above the Mississippi Fan Fold Belt are very thin. In this situation, the highs on the sea floor above the Mississippi Fan Fold Belt formed while the Middle-Late Miocene was eroded. Nearly 1.5 seconds or over 2 km of the Middle Miocene was eroded in the example shown in Figure 7-5b.
Note: Figure 11-3a is included in the pocket together with the plates and maps.
Note: Figure 11-3b is included in the pocket together with the plates and maps.
11.5. Summary

Submarine erosions form various regional and local angular unconformities. The erosion mechanism is not the subject of this study. It is generally accepted that the erosions related to canyons may be related to sea-level fall (e.g. Vail, 1987). The erosion at the base of the deep marine fans is due to turbidity currents. The deep marine fans mostly develop during sea-level lowstands (e.g. Vail, 1987). The regional deep marine erosion during times of starved sedimentation may not be directly related to sea-level changes which typically occur only in the range of -100 to 250 m (lowest and highest sea levels relative to present sea level, according to Haq et al, 1987). Thus the deep sea contour currents might be the main cause of the erosions found near the condensed section of mid-Cretaceous-mid-Oligocene, Florida Escarpment, the top of the Mississippi Fan Fold Belt, the Sigsbee Escarpment and other sea floor highs. Very little is known about Neogene deep-water erosional processes during the Neogene. A first step toward a better understanding of these processes would be a study showing the distribution in time and space of deep-water erosion in the Gulf of Mexico.
Chapter Twelve

Interaction of Salt Movement and Sedimentation

The distribution of Meso-Cenozoic sediments on the continental slope of the northeastern Gulf of Mexico has been complicated by the presence and movement of the mid-Jurassic Louann salt. The unevenly deposited sediments deform the underlying salt. In turn, deformation of salt changes the accommodation space for sediments over the salt. The geology of the northeastern Gulf of Mexico slope is a result of complex interactions between sedimentation and deformations salt. Sediment loading triggers salt tectonics which in turn influences sedimentary depositional patterns in a delicate feedback process.

12.1. Pre-mid-Cretaceous

Prior to the mid-Cretaceous transgression (Turonian, 91.5 Ma), most of the sedimentation was dominantly related to carbonates deposited on salt. The process began during the Late Jurassic with the deposition of Norphlet sand and Smackover carbonates. As a first result, salt rollers formed. Under the basinward thinning Norphlet and Smackover sediment load, the underlying salt moved downdip and basinward where the salt had little sediment cover. Late Jurassic structures on the platform ceased to be active as soon as salt was depleted. As sedimentation continued during the early Cretaceous, the deformation of sediments shifted basinward over thicker salt that also moved basinward.

By the early Cretaceous, extensive carbonate platforms were built around the Gulf of Mexico (see Sohl et al, 1991). Any salt that originally was deposited below the carbonate platforms probably moved basinward and accumulated under the slope. Since then, the interaction between salt and sedimentation occurred mostly over the mid-
Cretaceous slope and extended to the basinward limit of the salt basin. The formation of salt massifs responding to sedimentation on the mid-Cretaceous slope resulted in the uneven sediment distribution. Map 3A shows the resultant isopach of pre-mid-Cretaceous sediments in the area. The isopachs change greatly. The influence of the underlying salt on sediment distribution is obvious when compared with the sediments deposited over a salt-free oceanic basement to the south. In turn, Map 3B reflects the deformation of the underlying salt. Most of the original Jurassic salt layer was deformed by the sediments shown on Map 3A. Various structures were created within the deformed sediments, e.g. turtle structures (Figure 4-4), pseudo-clinoforms (Figure 4-6) and other structures caused by salt movements (Figures 2-3, 7, 8 and 9).

12.2. Mid-Cretaceous to mid-Oligocene

Mid-Cretaceous (91.5 Ma) - mid-Oligocene (30 Ma) is a period of sediment starvation. The isochron of this interval on Map 9 shows only minor changes across the study area whether they are above the salt basin or else over the salt-free area. Autochthonous salt structures were stable when the rate of sedimentation was very low. The condensed interval separates the pre-mid-Cretaceous and Oligocene-Present tectonic and sedimentary styles as documented by the regional profiles on Plates I-V and Plates VII-VIII.

12.3. Mid-Oligocene to Lower Miocene

Following the long period of sediment starvation, major depocenters shifted from the western Gulf of Mexico to the east into the study area to provide increased sediment loads. During the mid-Oligocene (30 Ma) - Lower Miocene (15.5 Ma), sedimentation modified the salt movements most importantly in the northwest corner of the Mississippi
Canyon area as shown on Map 11. Especially across the Mississippi Fan province, the sedimentation remained uniform. Without substantial salt movements during this early phase, the slope area behaved much like the regular slope of a passive margin. I expect that lowstand basin floor fans might have developed near the area of the present Mississippi Fan Fold Belt.

12.4. Middle-Miocene

The Middle Miocene was tectonically a very active period in the history of the northeastern Gulf of Mexico. The activity is all related to the interaction of salt under rapid differential sedimentary loading. On Map 12 please note the contrast between the isochrons over the salt basin and the salt-free area. With rapidly increasing sedimentation, much of the previously deformed salt began to develop into large diapirs on the continental slope. As a result of this diapirism and the lateral downslope displacement of sediments, the Mississippi Fan Fold Belt formed during this time. On Map 12, we can see the thinning of sediments over the Mississippi Fan Fold Belt. North of the fold belt the isochron of sediments varies greatly due to salt diapirism. Local basins formed as salt moved to feed local diapirs. In contrast, in the salt-free area, sedimentation remained very stable. The Mississippi Fan Fold Belt formed and first ceased to be active in the western part of the fold belt. In the eastern part of the area, the early Middle-Miocene (15.5-13.8 Ma) was similar to the Lower Miocene because salt activity was mild and the Mississippi Fan Fold Belt had not yet formed. Some basin floor fans may have developed in the eastern Mississippi Fan Fold Belt during the early Middle Miocene (15.5-13.8 Ma) before large diapiric salt structures and the fold belt were formed. For exploration purposes, Oligocene-Lower Miocene and lower Middle Miocene deep-water clastics may offer attractive possibilities for good reservoir sands.
12.5. Upper Miocene

During the Late Miocene, the first large allochthonous salt masses began to form on the slope. As large amounts of salt moved from an autochthonous position to form allochthonous salt structures near sea floor, major salt withdrawal basins formed behind the allochthonous salt as shown by Map 13. By the time salt began to spread, the Mississippi Fan Fold Belt ceased to develop, as discussed in Chapter Seven. Large amount of sediments were trapped in the salt withdrawal basins behind the allochthonous salt structures. As a result only small amounts of sediments reached the Mississippi Fan Fold Belt area as illustrated by Map 13. Thus, it is expected that most sands of Late Miocene age are trapped in the primary withdrawal basins to the north of the extensive allochthonous salt.

12.6. Pliocene

By the Pliocene, most of the salt was redistributed in the form of allochthonous sheets. The primary salt withdrawal basins began to provide less accommodation space for sediments. As the Mississippi began to dump large amount of sediments in the delta and the fan, the allochthonous salt began to redeform under the clastic sediments. Thus, large new secondary withdrawal basins formed on the continental slope. These basins accommodated large amounts of Pliocene sediments as shown on Map 14, and we can see that the Mississippi Delta and Fan in large part are built on top of the highly deformed allochthonous salt. In a feedback system, the Pliocene deltaic deposits deformed the allochthonous salt, and the distribution of Pliocene Mississippi Fan deposits in turn was highly influenced by the allochthonous salt deformation.
12.7. Pleistocene to present

Pliocene styles of deformation continued their influence into the Pleistocene. Sediments continued to be deposited on top of the allochthonous salt as shown on Map 15. During the Pleistocene, large amounts of sediments also bypassed the upper slope salt province and were deposited in the lower slope and abyssal plain forming the Mississippi Fan we see today (e.g. Weimer, 1989). Map 1 shows the bathymetry of the present slope. We observe the Mississippi Canyon that leads to the upper Mississippi Fan. As a result of the mostly Pliocene-Present interaction of sedimentation with allochthonous salt, we see the resultant sediment distribution on top of allochthonous salt in Map 8 and the deformed allochthonous salt structure as shown on Map 7. On Map 1 we can see that the deformed allochthonous salt forms highly irregular intra-slope structures that influence modern sedimentation.

12.8. Conclusion

The Meso-Cenozoic history of the northeastern Gulf of Mexico is the history of interaction of differential sediment loading and salt deformation. The ultimate configuration of the continental slope of the northeastern Gulf of Mexico will continue to be determined by the interaction of sedimentation with salt movement.
Chapter Thirteen

Salt Tectonics of the Northern Gulf of Mexico and Shale Tectonics of Offshore Nigeria - Similarities and Contrasts

With differential loading, salt and under-compacted shales control the tectonics on the otherwise stable passive margins. Salt and shale structures influence extension and contraction on many passive margins. Regional tectonics of the well-developed salt tectonic province of the northern Gulf of Mexico are compared and contrasted with the well-developed shale tectonic province of the Niger Delta.

Recent high-resolution deep mutichannel seismic profiles make it possible to see much of the complete system of both study areas (Hall and Wu, 1992). By comparing and contrasting salt and shale tectonics, we can better focus on the linkage between salt or shale tectonics and extension or contraction on these passive margins.

13.1. Structural styles and evolution of the northwestern Gulf of Mexico

The Gulf of Mexico is one of the best known basins in the world. Many papers have described the tectonic development of the basin (e.g. Humphris, 1978; Buffler and Sawyer, 1985; Salvador, 1987; Worrall and Snelson, 1989; Wu et al, 1990b; Sawyer et al, 1991; Weimer and Buffler, 1992). A regional seismic line drawing across the entire Texas continental margin (see Figure 13-1 for location) shows typical structural styles of the northwestern Gulf of Mexico (Plate X). Plate X shows structures from near the mid-Cretaceous shelf margin across the continental shelf and slope to the Perdido Fold Belt. This regional transect is supported by two types of seismic data. In the onshore and shelf areas, good quality mutichannel 2-D seismic data (Courtesy of TGS-CALIBRE
Figure 13-1. Regional tectonic elements of the northern Gulf of Mexico and the location of study area (after Ewing, 1991). Both the Mississippi Fan Fold Belt and the Perdido Fold Belt formed during a short period of time near the basinward limit of mid-Jurassic salt. Both fold belts are no longer active today. Updip to the fold belts there are large salt sheets and extensional systems that are decoupled at various levels.
Geophysical Co.) are used. On the slope, the interpretation is based on a special 18.0-20.0 seconds experimental seismic Line GBRS-1 acquired by the joint Gulf of Mexico Regional Study program of TGS-CALIBRE Offshore Co. with GECO-PRAKLA Geophysical Company, Inc. and the Department of Geology and Geophysics of Rice University sponsored by the oil industry. The deep seismic Line GBRS-1 allows us to see some deep reflections from underneath the extensive allochthonous salt.

Several time markers are correlated based on well data and published sources (e.g. Worrall and Snelson, 1989). The age in million years is based on Haq et al (1987). The base of mid-Jurassic salt (158.5 Ma, Wu et al, 1990a) and top mid-Cretaceous (91.5 Ma, Wu et al, 1990a) are correlated because of their unique seismic character. Surfaces of top Cretaceous (68 Ma), Lower Eocene (49.5 Ma), mid-Oligocene (30 Ma), Lower Miocene (15.5 Ma), Middle Miocene (10.5 Ma), Upper Miocene (5.5 Ma) and middle Pliocene (3.0 Ma) are correlated on the base of biostratigraphic information from wells in the upper slope area. The correlation over the lower slope is based partly on Worrall and Snelson (1989) and partly on seismic character (e.g. the top and base of mid-Jurassic salt). The allochthonous salt is interpreted by its seismic character.

13.1.1. Salt structures

Salt and related structures occur throughout the entire section (Plate X). Both autochthonous and allochthonous salt structures (e.g. Bally, 1981; Worrall and Snelson, 1989; Wu et al, 1990b; Liro, 1992) are observed. Most of the original mid-Jurassic salt bed is either very thin or has been removed from its original area, leaving behind welds (Jackson and Cramez, 1989) involving the sediments originally overlying and underlying the salt. An exception to this is the Perdido Fold Belt where thick autochthonous salt forms the core of the folds. The base of the allochthonous salt dips seaward from onshore to the shelf break. From there the base of salt stays relatively flat with a slight decrease in
depth over the lower slope. The base of the salt is a relatively smooth surface with no clear indication of major faulting. Velocity pull-ups shown in the sub-allochthonous surfaces are caused by shallow high velocity allochthonous salt structures.

An allochthonous salt sheet which covers the entire continental slope is the most striking feature of the cross section (Plate X). From previous studies (e.g. Bally, 1981; Worrall and Snelson, 1989; and Wu et al, 1990b) we know that the allochthonous salt evolved from the original mid-Jurassic autochthonous salt under specific conditions, involving thickness and drainage area of salt, density inversion, and differential loading in a slope environment (Wu et al, 1990b). The allochthonous salt sheet on this profile formed about late Eocene to mid-Oligocene (i.e. earlier than in the eastern Gulf of Mexico) as shown by the age of the sediments underlying and overlying the allochthonous salt in Plate X. Since then, salt has been spreading downslope due to differential loading and gravity spreading mostly under a thin sediment cover. A landward inclined salt weld underneath the outer shelf is interpreted as part of a depleted large salt feeder stock or the wall of an extensive allochthonous salt sheet. The leading edge of the spreading salt sheet deforms the sea floor, forming a sea floor scarp (Sigsbee Scarp, Buffler, 1983). The base of the allochthonous salt sheet cuts across underlying sediments and steps upward. The top of the allochthonous salt is progressively more deformed in a landward direction. Several supra-allochthonous-salt basins are formed.

13.1.2. Extensional systems

Several extensional systems sole out at different levels on the cross section (Plate X). None of the faults cut through the entire sedimentary section. Growth faults shift progressively seaward. The oldest and most landward faults decouple at the top of or within the thin autochthonous salt or salt weld. Some of the faults decouple within Upper Cretaceous shales but without forming large shale structures. The rapid sedimentation
increased the load on the Lower Paleogene slope causing a corresponding basinward autochthonous salt movement under differential loading, which is interpreted as the cause of the faulting. This set of faults is restricted to the onshore and shelf areas and ceased to be active after Lower Eocene time (49.5 Ma).

The second set of extensional faults soles out near the top of the Lower Eocene (49.5 Ma) shales. Again no significant shale structures are associated with this system. These faults are situated behind and merge at its northern end with the base of the allochthonous salt sheet. I interpret this set of faults as due to extension associated with the withdrawal of salt and the formation of an allochthonous salt complex. Most of the faults of this system ceased to develop after the late Oligocene.

A third system of faults formed since mid-Oligocene. These faults decouple on top of and perhaps within the allochthonous salt. They form together with the emplacement of the allochthonous salt beginning at about mid-Oligocene. This set of faults is the direct result of the seaward spreading of the allochthonous salt sheet under differential loading as described by Worrall and Snelson (1989). The age of the faults reflects the timing of sediment loading and the deformation of the allochthonous salt. A large mid-Oligocene-Pliocene depocenter and associated growth faults developed over the northern end of the allochthonous salt sheet. This group of growth faults becomes progressively younger basinward to the south.

13.1.3. Perdido Fold Belt

The Perdido Fold Belt is located on the lower slope of the Texas continental margin (Blickwede and Queffelec, 1988; Buffler, 1989; Worrall and Snelson, 1989; Weimer and Buffler, 1992). The southern margin of the fold belt coincides with the basinward zero edge of the mid-Jurassic autochthonous salt. The shortening of the fold belt occurred mostly during the Late Eocene to mid-Oligocene as indicated by the updip convergence of
sediments during this time interval. Before this period, the sediments are essentially isopachous and show no sign of shortening. The section from mid-Oligocene (30 Ma) to mid-Pliocene (3.0 Ma) generally shows onlap and infill of the synclines and mild growth on the flanks of the anticlines (see Plate X). After mid-Pliocene (3.0 Ma), the salt cored fold is uplifted by the growth of the salt anticline. Most of the shortening in the Perdido Fold Belt occurred during the Late Eocene to mid-Oligocene and ceased to develop after that time. Thus, the Perdido Fold Belt formed during the same time interval when the autochthonous salt began its diapiric rise. The shortening across the fold belt ceased when the allochthonous salt to the north began to spread and to be emplaced as sheets within shallow sediments. Note that the deformation began in the south and proceeded north, as opposed to the "in sequence" deformation so frequently observed in the classical folded belt. Much of the Perdido Fold Belt developed earlier that the Mississippi Fan Fold Belt, which developed during the Middle-Late Miocene.

13.1.4. Summary

Thick mid-Jurassic salt was deposited in the northern Gulf of Mexico Basin. Differential loading of this salt combined with density inversion and followed by gravity spreading led to the formation of extensive allochthonous salt masses on the Texas continental slope. A series of extensional fault systems developed in response to different stages of salt movement. Three major sets of extensional systems with separate decoupling levels (i.e. autochthonous salt, top of the Lower Eocene shale and top of allochthonous salt), of different extent and of various ages (i.e. pre-Eocene, Eocene-Oligocene and post Oligocene) developed during the Cenozoic. I conclude that these different extensional systems show little obvious and direct relationship with the compressional Perdido Fold Belt because a) the fold belt was active for only a brief period during the Late Eocene to mid-Oligocene while extension occurred since the early Tertiary and lasted until today; b)
there are four different decoupling levels (top of autochthonous salt, top Cretaceous, top Lower Eocene and top allochthonous salt) for the extensional systems and only one
decoupling level (top of autochthonous salt) for the Perdido Fold Belt; and c) The oldest
Paleocene-Lower Eocene extensional system that shares the same Jurassic salt decoupling
level with the Perdido Fold Belt did not cause any shortening in the Fold Belt because the
fold belt did not form until Late Eocene to mid-Oligocene. Thus the Perdido Fold Belt is
formed as the direct consequence of rise of the diapirs that were the feeder stocks or walls
for the allochthonous salt similar to the model proposed for the development of the
Mississippi Fan Fold Belt in the northeastern Gulf of Mexico (Wu and Bally, 1992). As
shown by Wu and Bally (1992), the fold belt therefore also formed during the rise of the
large salt diapirs. Thus the compression of the folds is due to the intrusion of salt and
precedes the downslope movement of sediments overlying the autochthonous salt.

13.2. Structural styles and evolution of the continental slope offshore Nigeria

The offshore Niger Delta is a "classical" shale tectonic province. The geology of the
Niger Delta has been described in many papers (e.g. Mascle et al, 1973; Beck and Lehner,
1975; Lehner and de Ruiter, 1977; Knox and Omatsola, 1989; Doust and Omatsola,
1990). Figure 13-2 (after Knox and Omatsola, 1989) shows the tectonic provinces of the
Niger Delta and the location of the regional seismic profiles shown in this paper. The
Neogene Niger Delta is underlain by thick Tertiary over-pressured marine shales. Under
differential loading due to rapidly deposited sediments, large growth fault-bounded
depobelts formed on the shelf (Knox and Omatsola, 1989). However, shale ridges, diapirs
and inter-diapir depocenters are more typical for the slope. Finally, the basinward end of
the delta is marked by a distinct toe thrust system.
Figure 13-2. Regional structural elements of the Niger Delta and location of seismic profiles. Compressional thrust formed at the toe of the Niger Delta since Miocene (after Knox and Omatsola, 1989). The toe thrusts are still active today. Large shale diapirs and extensional growth faults developed in the updip direction of the toe thrusts. The seismic profiles shown are provided courtesy of TGS-Calibre Geophysical Company.
Some of the detailed aspects of shale tectonics in this area are illustrated by line drawings of several regional seismic lines (Plate XI) from a grid of data obtained by TGS International Geophysical Company and MABON Limited. Only a few poorly calibrated time surfaces are interpreted and tied at few points on DL1, DL2, DL3 and SL1 in Plate XI. DL4 is correlated based only on seismic character. The age determination of "Lower Pliocene" (4.2 Ma), "Middle Miocene" (10.5 Ma ?) is approximate and based on proprietary well information in the upper slope area and on the correlation of a TGS-CALIBRE regional sequence stratigraphic project and published sources (Haq, et al, 1987; Beck and Lehner 1975; Knox and Omatsola, 1989; Doust and Omatsola, 1990). The "Paleocene" top is only a guess because no direct correlation with well information can be made across the mobile shale province in the middle slope. This surface is characterized by low frequency and high amplitude reflectors. It can be recognized for most of the slope area. Basement is recognizable on seismic data as a very strong and low frequency reflector below which there are no reflections. The basement is thought to be an Albian oceanic crust developed during the opening of the Atlantic Ocean (Knox and Omatsola, 1989; Doust and Omatsola, 1990). For most of the area the basement underlying the delta is smooth. It dips gently landward (Line DL4 in Plate XI) except near the Charcot Fracture Zone where the basement is associated with a high relief as shown on Lines DL1 and SL1 in Plate XI. This basement relief has affected the position and style of the toe thrust (Line DL1, Figure 13-2; Knox and Omatsola, 1989; Masce et al, 1973).

From the cross sections on Plate XI, we can see that from the shelf to the lower slope, the structural styles change from an extension-dominated style to a diapiric shale province and finally to the imbricates and toe thrusts of the lower slope and rise. The sections show the relationship between shale structures, extension, and contraction in the Niger Delta.
13.2.1. Shale structures

Widely distributed marine shales deposited since the late Cretaceous underlie the entire Niger Delta (e.g. Mascle et al, 1973; Lehner and de Ruiter, 1977; Knox and Omatsola, 1989). Since "Paleocene" the load of the rapidly developing Niger Delta causes and deforms the over-pressured shales. Thus over-pressured shale has been squeezed progressively farther seaward under and in front of a prograding delta load (Dailly, 1976; Knox and Omatsola, 1989) forming large shale ridges and diapirs as shown on Lines DL1, DL2 DL3 and SL1. As sediments continue to prograde, the older shale ridge is deformed and pushed farther seaward. We see that some local basins are being developed on top of the shale massif (e.g. Line DL1) as sedimentation continues. As most of the shale is squeezed in front of the sediment load to form of large shale massifs, some deformed shales remain behind and are trapped under the delta, forming individual shale ridges in between two depobelts (Knox and Omatsola, 1989).

Limited shale overhangs are visible on the seaward advancing shale massif. Seen on the profiles Line DL1, DL2, DL3 and SL1, the shale massif tends to separate areas with normal faults from areas with toe thrusts. Most of the large shale structures are involved in a toe thrust system suggesting that large shale structures are under compression, being squeezed seaward from under the prograding delta. Line DL4 does not show any large shale diapir. It is located between large shale structures.

13.2.2. Extensional systems

Large extensional systems began to form during the early Middle Eocene stage of the delta development (Knox and Omatsola, 1989; Doust and Omatsola, 1990). A series of growth faults soles out within the mobile marine shale and affects deltaic paralic sediments (Figure 13-3). The growth faults are formed together with the deformation of the underlying marine shales in response to large loading of prograding deltaic sediments
(e.g. Beck and Lehner, 1975; Knox and Omatsola, 1990). Most of the extensional systems are located onshore and on the continental shelf as shown in Figure 13-3. The oldest growth fault system in the landward direction ceased to develop as most of the mobile shales were squeezed to the slope area. The growth fault systems become progressively younger seaward according to Knox and Omatsola (1990). Also most of the faults dip toward the sea (e.g. DL1 and DL2 on Plate XI) but note that some major "conjugate" faults dip landward (e.g. DL4 on Plate XI).

On the slope, where our data are located, we can see growth faults being developed behind and on top of the shale massif. These growth faults are the youngest of the delta. They show mostly the Pliocene-Present expansion of sediments. Dominantly seaward dipping growth faults decouple within the mobile shale. Some small-scale tension faults are also present. On Line DL2 we can see that a Pliocene-Present depocenter or depobelt (Knox and Omatsola, 1989) is developing. Landward it is bounded by a growth fault and seaward by a shale massif. The expansion of the growth fault is translated to the coeval deformation of shale massif, and the contractional toe thrusts. However, some toe thrusts ceased to be active while the shale massif continues to grow.

13.2.3. Toe Thrusts

A spectacular toe thrust system occurs at the base of the Niger Delta slope (Figure 13-2, e.g. Maascle, 1973; Beck and Lehner, 1975; Lehner and de Ruiter, 1977; Mandl and Crans, 1981; Knox and Omatsola, 1989; Doust and Omatsola, 1990). The toe thrusts are situated seaward of the shale massif and landward of the undeformed deep marine deposit. Based on excellent seismic data, Plate XI shows typical toe thrusts in front of the Niger Delta. The observed shortening began during the "Late Miocene" and has been active since then. Plate XI shows that on the slope the active toe thrusts are coming close to the sea floor. The toe thrust belt is decoupled within the landward portion in the deformed
Figure 13-3. Growth faults on mobile shale on the shelf offshore Nigeria (After Knox and Omatsola, 1989). Extensive growth faults developed on top of the mobile marine shales.
shale, which sometimes appears to involve the Paleogene and which soles out close to top of the oceanic basement. In the seaward portion of the thrust belt, the decoupling level ramps up from the basement to near the interpreted top of the "Paleocene" surface. Comparing Lines DL1 and DL4 we can see the influence of basement geometry on the styles of toe thrusts. The basement relief shown on Line DL1 is part of the Charcot Fracture Zone. The presence of the basement high acts as a mechanical boundary where the shortening is concentrated as stacked thrust imbricates. The effect of the basement relief and the lateral ramp of the thrust are also observed on the strike line SL1 on Plate XI. On Line DL4, the basement is slightly inclined seaward following depth conversion. The shortening is thus spread out over an area that is 100 km wider than the area near the Charcot Fracture zone. An indentation of the leading edge of the toe thrust near the Charcot Fracture Zone is formed as a result of the basement relief (Figure 13-2). Line DL4 is located in between large shale massifs and diapirs. The extension on the shelf and upper slope is translated into shortening of the toe thrusts through the mobile marine shale section.

13.2.4. Summary

The seismic profiles shown in Plate XI illustrate the relationship between extensional growth faults, deformed mobile shale and contractional toe thrusts on the continental slope of the Niger Delta. From onshore to the lower slope, the structural styles change from stabilized buried extensional growth faults to active growth faults, to highly deformed shale massifs and diapirs, and toe thrusts. Various stages of extensional growth faults developed since Eocene. The growth faults sole out within the deformed marine shale. Thus extension is translated downdip through ductile marine shales into the diapiric shale massif and shortening in the toe thrust. The deformed mobile shale has been moving seaward to form large shale massifs and diapirs under the loading of prograding delta. Toe
thrust systems have been active since the Late Miocene. Increased shortening results from seaward movement of shale under the prograding delta. The basement relief of the Charcot Fracture Zone causes the concentration of shortening within the toe thrust belt. The tow thrust system decouples mostly within the Paleogene marine shale. Figure 13-4 from Knox and Omatsola (1989) shows a model for the development of the extensional system over mobile shale. The development of a toe thrust system is only briefly mentioned. From the recent seismic data as illustrated in Plate XI, a more detailed analysis of toe thrust deformation is possible.

13.3. Discussions and conclusions

A comparison of the structural styles documented by seismic data in the northern Gulf of Mexico and the Niger Delta reveals the similarities and differences between salt and shale structures and their relations to associated extensional and contractional structures.

13.3.1. Tectonic setting

The northern Gulf of Mexico and the Niger Delta are deltaic systems situated on passive continental margins. The basement is not significantly involved in the tectonics of either basin. The tectonic activities involve prograding clastic sediments over unstable salt or mobile over-pressured shale substrata. The Pliocene-Present rate of sedimentation at the shelf margin near the central part of the Niger Delta reaches over 1.2 mm/year (4 seconds two way time in 4.2 million years at seismic velocity of 2.5 km/second). The overall slope surface was about 1.6 degrees with local variations (Plate XI). In the northwestern Gulf of Mexico (Plate X) the slope is about 5 degrees on average. The highest rate of sedimentation on the slope is about 0.6 mm/year within the supra-
Figure 13-4. Conceptual model for the development of depobelt and shale structures (from Knox, Omatsola, 1989). Growth faults developed as mobile marine shales were squeezed basinward under prograding delta.
allochthonous-salt basins during the mid-Pliocene-Present. With a steeper slope and higher rate of sedimentation, the Niger Delta slope is gravitationally more unstable than the slope of the northwestern Gulf of Mexico.

13.3.2. Salt versus shale structures

Salt and shale are ductile and both deform under differential loading. Gravity spreading under differential loading is common for salt and over-pressured shale tectonics. Thus similar diapiric structures such as ridges, domes and large massifs are found in deformed shale and salt. But the large-scale allochthonous structures are unique to salt, especially in the northern Gulf of Mexico salt basin. The strong density difference between salt and compacted and under-compacted sediments allows salt to rise higher in the section due to buoyancy forces. Salt appears to be more mobile in the Gulf of Mexico than in the over-pressured shale of the Niger Delta. This may be related to the rheology difference between salt and over-pressured shale. The mobility of salt does not reduce within the sediments in the process of deformation, while the shale loses its over-pressure after extrusion and loss of pressured fluid. Today in the Gulf of Mexico, much of the salt becomes allochthonous where as in the Niger Delta shale structures remain deeply rooted.

13.3.3. Extensional systems

Extensional faults dominate in both areas. Extensional systems of varying ages extend from onshore to the slope. As we can see in both the northern Gulf of Mexico and in the Niger Delta, extensional systems are situated over and behind salt or mobile shale massifs. In the northern Gulf of Mexico, because there is autochthonous and allochthonous salt at different levels, there are different decoupling levels. The extension of growth faults is accommodated by the withdrawal and seaward spreading of salt in both autochthonous and allochthonous positions. Little or no extension is translated into the
minor contractions of the Perdido Fold Belt. Because shale structures are deeply rooted in the Niger Delta, there is basically one decoupling level in the marine shale. Extension in the Niger Delta is accommodated by the deformation of mobile shale and the toe thrusts as illustrated by regional profiles in Plate XI. Thus overall shortening is limited in the Perdido Fold Belt but quite substantial in the Niger fold belt.

13.3.4. Contractional systems

Contractional systems are present in the lower slope of the northern Gulf of Mexico and in the Niger Delta. The Perdido Fold Belt is limited to the southern edge of the mid-Jurassic salt basin. It was active briefly during the late Eocene to mid-Oligocene. The fold belt decoupled at the top of the autochthonous salt. Limited shortening is the result of strain concentration on the downslope edge of the mid-Jurassic basin. Our interpretation is that the shortening is transmitted from the large rising salt diapirs that formed in response to under differential loading during an early stage of allochthonous salt evolution similar to the development of the Mississippi Fan Fold Belt in the northeastern Gulf of Mexico as proposed by Wu and Bally (1992). Once large allochthonous salt structures began to form, the space provided by salt withdrawal from both the autochthonous level and from the feeder stocks accommodates the increased sediment thickness. Thus since mid-Oligocene the fold belt ceased to develop while the extension updip to the fold belt continues and is transferred to the allochthonous salt. In contrast, the toe thrusts in the Niger Delta have been forming since Miocene time. With the addition of sediments, shortening in the toe thrust increases. The decoupling level in the Niger Delta marine shale is less confined and thus differs from the limited distribution of salt in Gulf of Mexico. Part of the extension up-slope becomes the shortening of the toe thrusts in the Niger Delta. Overall shortening in the Niger fold belt is substantially more than in the Perdido Fold
Belt. The most basinward toe-thrusts form earlier in the Niger Delta, and the focus of deformation proceeds from the seaward side to the land.

13.3.5. Conclusions

The presence of salt or over-pressured shale is responsible for a very complex system of salt and shale structures and for extensional and contractional systems on the otherwise stable passive continental margins of the northwestern Gulf of Mexico and the Niger Delta. The two study areas show similarities and differences in some aspects.

a) Both salt and shale deform in a ductile manner under differential sediment load. They both form relatively "autochthonous" structures such as ridges, domes, massifs and diapirs. Large allochthonous salt sheets covering a large part of the continental slope in the northwestern Gulf of Mexico are unique to salt. The allochthoneity of large salt sheets is due to density inversion of salt under sediment loading on the slope. There are no equivalent allochthonous shale structures because there is a less significant density difference between over-pressured shale and other clastic sediments. It is also likely that with the rise of shale diapirs, the over-pressured shales are relieved.

b) Both the salt and the shale provinces show widespread extensional growth fault systems. Three major growth fault systems of various ages, four separate decoupling levels and different amounts of extension are associated with autochthonous and allochthonous salt movement and distribution in the Gulf of Mexico. Growth fault systems of various ages exist also in the Niger Delta. But the difference is that they all share and merge into the marine pro-delta shales in an ill-defined manner.

c) Contractional fold and thrust systems exist in both the northwestern Gulf of Mexico and in the Niger Delta. The Perdido Fold Belt in the Gulf of Mexico was active during a short period (mid-Eocene-mid-Oligocene) relative to the entire history of the Gulf margin, and folding ceased abruptly when the salt was separated from its feeder
stocks to form allochthonous sheets. Afterwards, the up-slope extension increased and was directly transferred into the allochthonous salt. The fold belt formed along the basinward edge of the mid-Jurassic salt basin as a combined effect of salt movement under differential loading and downslope displacement. The fold belt terminated with the spreading of allochthonous salt. In the case of the Niger Delta, deformation of the shale massif and shortening in the toe thrust are directly related to the extension caused by an unstable prograding slope. The toe thrusts have been active since their initiation in Late Miocene. Shortening in the toe thrusts increases as the delta continues to prograde. Toe thrusts and shale massifs probably differ in the ductility of shale due to less over-pressure at the base of the delta, caused slow rate of sedimentation.
Chapter Fourteen

Meso-Cenozoic Evolution of the Northeastern Gulf of Mexico

The sequence stratigraphic and structural analyses of well imaged seismic profiles together with reasonable well controls lead to the following conclusions regarding the tectonic history of the continental slope offshore Louisiana. As summarized in Figure 14-1, the relationship between salt, sediment loading, extensional system and contractional systems are similar in both the eastern and western Gulf of Mexico.

In the northeastern Gulf of Mexico, the Mississippi Fan Fold Belt was formed due to the lateral displacement of slope overburden by actively rising diapirs in response to the increased sediment loads of the Middle Miocene and Late Miocene. The Mississippi Fan Fold Belt ceased to be active when salt began to spread near the sea floor within the slope sediments. Further increased sediment loads and extension upslope did not keep the fold belt active. Large extension to the north of the spreading salt is accommodated by salt withdrawal from both autochthonous salt and allochthonous salt.

In the northwestern Gulf of Mexico, in response to the large Eocene and Oligocene sediment loads, salt was deformed and began to pierce through the thick overburden. The Perdido Fold Belt was formed during the late Eocene and Oligocene due to the lateral displacement of overburden by active diapirs on the slope. Also, the updip extension is mostly compensated by the deformation of both autochthonous and allochthonous salt.

A model on the development of salt, extensional structures and contractional structures is summarized in Figure 14-2 for the northeastern Gulf of Mexico. Some key processes proposed in the model may be simulated in the laboratory using analog or numerical experiments.
Figure 14-1. Summary of regional depocenters and their relationship to salt structures, extensional and compressional systems of the northern Gulf of Mexico (after Ewing, 1991; Salvador, 1991a, 1991b; McFarlan and Menes, 1991; Sohl et al, 1991; Galloway et al, 1991). The Perdido Fold Belt was formed along the basinward limit of mid-Jurassic salt during late Eocene and Oligocene due to updip massive salt diapirism in response to Eocene and Oligocene overburden. The Mississippi Fan Fold Belt was formed later along the basinward limit of mid-Jurassic salt during Mid-Late Miocene due to updip massive salt diapirism in response to Mid-Late Miocene rapid sedimentation. Both fold belts ceased to be active when the updip allochthonous salt began to spread within younger sediments near sea floor. The increased Pliocene and Pleistocene sedimentation of the Mississippi Delta did not reactivate the Mississippi Fan Fold Belt.
Figure 14-2. Schematic Meso-Cenozoic structural evolutionary stages of the northeastern Gulf of Mexico. (a) Development of salt massifs, local allochthonous salt and primary welds on the slope. (b) Salt structures remained stable during the mid-Cretaceous and mid-Oligocene condensed sedimentation interval. (c) Reactivation of salt structures as depocenter shifted to the northeastern Gulf of Mexico. (d) Massive active diapirism upslope and the resultant downdip
Mississippi Fan Fold Belt near the basinward limit of the mid-Jurassic salt. (e) Early spreading of the primary allochthonous salt, cessation and erosion of the Mississippi Fan Fold Belt, development of primary welds, primary withdrawal basin and associated growth faults. (f) Development of large primary welds, primary and secondary withdrawal basins and associated growth fault systems. (g) Development of secondary allochthonous salt, large secondary and tertiary withdrawal basins, secondary, tertiary and higher order welds.
14.1. Conclusions

Distribution of the Jurassic Louann salt, the depositional pattern of post-salt sediments, and the presence of a continental slope are the key elements of the Meso-Cenozoic tectonics in the northeastern Gulf of Mexico. Various stages of salt movement control the post-mid-Jurassic regional and local sediment distribution and structural styles (e.g. autochthonous and allochthonous salt structures, regional and counter-regional growth faults and the Mississippi Fan Fold Belt).

The mid-Jurassic (i.e. Louann Salt and time equivalent) was deposited on a relatively smooth regional unconformity. The salt thickens toward the central Gulf of Mexico, and pinches out updip to the north and east and diminishes downdip to the south near a generally E-W trending transitional-oceanic crust boundary. No major faults offset the base of the mid-Jurassic salt basin. Post-salt sediment loading interacts actively with salt deformation in a complex feedback process. Four basic episodes of Meso-Cenozoic tectonics can be summarized for the northeastern Gulf of Mexico.

1) From its mid-Jurassic deposition to the end of Early Cretaceous, salt was deformed constantly by sediment loading. Salt structures such as domes, anticlines, rollers and massifs are the dominant structural forms of this period. Structures such as local growth structures, primary welds, pseudo-clinoforms and turtles formed as the sedimentary record of salt deformation. Peripheral fault systems formed near the updip limit of the salt basin. As indicated by the "pseudo-clinoforms", much of the salt was pushed forward under the sediment loading and concentrated near the present shelf to upper slope in the form of large massifs. Occasionally, some salt trapped under the thick sediment load was squeezed out to break through the overburden and form small scale allochthonous salt bodies.
2) During a very significant period of sediment starvation, between mid-Cretaceous (Turonian, 91.5 ma) and mid-Oligocene time (30 ma), previously formed salt structures were stabilized due to the lack of sediment loading.

3) From mid-Oligocene to Middle Miocene, salt structures were buried and reactivated by rapid sediment loading. Sands might be transported far into the lower slope as turbidites, forming basin floor fans before late Middle Miocene time. By the middle Middle Miocene, salt structures were drastically reactivated in response to increased sediment load. Active diapirism driven by buoyancy led to the formation of massive diapirs, salt walls and stocks and pushed the Mesozoic-Middle Miocene section downslope toward the basinward edge of the Jurassic salt basin. The contractional strains not accommodated by the primary salt withdrawal were transmitted to and concentrated along the basinward edge of the salt basin. It is here that salt, serving as a major decoupling layer, terminates downslope near the transitional-oceanic crust boundary. Thus, the Mississippi Fan Fold Belt formed along the E-W trending basinward edge of the salt basin as a result of these contractional strains. The shortening of the Mississippi Fan Fold Belt is less than about 2-3 km. The folding ceased by the early Late Miocene as the salt walls and stocks had made their way up through the overburden and began to emplace within the less dense sediments. The age of the fold belt gets progressively younger from west to east corresponding to the easterly shift of sediment depocenters and the corresponding upwelling of salt. The active period of the fold belt, as a whole, lasted no more than 10 million years from the Middle Miocene to the Late Miocene. During and after the formation of the Mississippi Fan Fold Belt, and updp from the fold belt, large primary withdrawal basins along with regional, counter-regional growth fault systems and tensional faults were formed as a result of massive salt withdrawal under the Mesozoic-Cenozoic overburden. Massive allochthonous salt structures thus formed mostly since the late Middle-Miocene. The bathymetric relief formed above rising salt structures and the
Mississippi Fan Fold Belt acted as barriers to sediment transport. Note that the Mississippi Fan Fold Belt underwent severe submarine erosion during the late Middle-Late Miocene.

4) During the Late Miocene and up to present time, large scale asymmetric allochthonous salt sheets continued to form and advanced downslope due to a combination of gravity spreading and differential loading. Part of the Mississippi Fan Fold Belt lies under the advancing allochthonous salt sheet. Primary withdrawal basins along with regional and counter-regional growth faults further developed on the shelf and upper slope during the Late Miocene and Pliocene because of salt withdrawal from the original salt layer that went to feed the allochthonous salt structures. Due to increased sediment loads, structures such as secondary withdrawal basins, basinward and landward dipping growth faults, local folds and reverse faults have been forming on top of the allochthonous salt sheets since their emplacement. In addition, secondary allochthonous salt structures have been forming on top of the primary allochthonous salt sheets since the Pliocene due to very rapid sedimentation rates. Some salt cores of the Mississippi Fan Fold Belt popped up since Pleistocene, forming detached salt pods. The bathymetric highs and lows created by salt movements controlled the distribution and deformation of the Mississippi Fan since its very beginning in Late Miocene time. Today, most of the Jurassic salt has transferred to form allochthonous sheets. Much of the autochthonous salt remained to form the core of the Mississippi Fan Fold Belt and diapirs in the eastern part of the deep Gulf, where both the original salt and the sediment overburden are relatively thin. The original mid-Jurassic salt layer has been evacuated to form a flat regional primary weld. Subvertical secondary welds are formed when salt in the feeder stocks and walls are evacuated. Extensive tertiary welds have been forming in place of the primary allochthonous salt bodies in response to continued sediment loading. Some quaternary and quintic welds are also forming at the feeders and on top of the secondary salt structures. Complex supra-allochthonous-salt secondary and tertiary withdrawal basins along with growth faults of various orientations
dominate the Pliocene-Present structural styles of the outer shelf to slope offshore Louisiana.

Interpretation of deep regional seismic data led to the conclusion that similar tectonic development processes may also be involved in the development of allochthonous salt, extensional growth faults, and the Perdido Fold Belt offshore Texas.

Deformation of over-pressured shale on the slopes produced large shale structures, growth faults and toe-thrusts as revealed by the seismic data from the Niger Delta, offshore Nigeria. The differences in mobility and deformation mechanisms of salt and shale resulted in contrasting styles of salt and shale deformation and different structural relationships between salt and shale structures and their related extensional and contractional systems.

14.2 Possibilities of simulating the Meso-Cenozoic tectonics using physical and numerical modeling

This study has documented in some detail the tectonic events and stratigraphy of the northeastern Gulf of Mexico using the best regional seismic data and well information available. With structural analyses and intensive mapping, we have good control of the timing and intensity of each major tectonic event in response to changes of sediment influx. A kinematic model of evolution is proposed. This model is a summary based on seismic evidence. I also try to use this model to explain the relationship and the dynamics of various tectonic phenomena in response to various phases of sediment loading.

A kinematic model based on the observation and analysis of the data was to be the first and the most important step toward the understanding of the tectonics of the area. Ideally, we would like to see kinematic models quantified by dynamic modeling. Although some dynamic parameters are taken into consideration in the proposed model, many
physical parameters such as the rock properties, boundary and initial conditions, temperature influence, and deformation conditions are not quantitatively defined. Ideally, with the observations and the proposed kinematic model, we should be able to set up physical and numerical experiments that simulate our observations. With more advanced modeling techniques, better equipment, better scaled materials and a more realistic setup, better mathematical formulation, more efficient numerical methods, and bigger computers, I expect that the tectonics history of the northeastern Gulf of Mexico could be modeled using scaled physical and/or numerical models. In the following, I explore the availability and limitations of some methods for future modeling studies of the salt related slope tectonics of the northeastern Gulf of Mexico.

14.2.1. Reviews of physical modeling

Various physical modeling experiments have been conducted to simulate the development of autochthonous and allochthonous salt structures since the middle of this century (e.g. Nettleton, 1934; Parker and McDowell, 1955; Talbot and Jackson, 1987; Jackson et al, 1988; Vendeville, 1987; Vendeville and Jackson, 1992; Talbot, 1992, Jackson and Vendeville, 1993). Various types of salt structures have been simulated.

Viscous fluid representation of sediments (e.g. Talbot and Jackson, 1987; Jackson et al, 1988; Talbot, 1992) versus brittle rock representation of overburden are two extremes in the analog experiments. The result of each assumption is different and each has generated some realistic structures. The fluid model usually produces realistic regional salt structures (Talbot, 1992). But fluid models could not reproduce faulting. Also due to the poor representation of the strength of overburden, the deeply buried salt structures, such as the Destin Dome, overlain by a thick carbonate overburden cannot be simulated.

Combining brittle overburden and a ductile salt model generated some realistic extensional faults (Vendeville, 1989; Vendeville and Jackson, 1991a) and compressional
faults (Jackson and Vendeville, 1993). However the brittle property of overburden may not always be true depending on the lithology. It may be practical on a carbonate platform as exemplified by the rotated slabs shown on Figure 2-3. However on the slope with rapid sedimentation of unconsolidated sediments, their experiments may not be realistic. Seismic data suggest that, in many cases, sediment overburden deforms in a ductile manner. A plastically deformed overburden may be more realistic.

14.2.2. Reviews of numerical modeling

Numerical modeling has been applied in simulating salt structures. Most of the experiments are still limited to simulated local salt structures.

Most of the numerical modeling for salt structure development is based on viscous fluid models (e.g. Danes, 1964; Daly, 1966; Woidt, 1978; Schmeling, 1987; Römer and Neugebauer, 1991). Diapirism is modeled as Rayleigh-Taylor instability in a salt-sediment system described by Navier-Stokes equations for viscous incompressible flow (Danes, 1964; For a summary of Rayleigh-Taylor instability, see Sharp, 1984). Various numerical methods are implemented in solving the Navier-Stokes equation. The finite difference "marker and cell" method (e.g. Welch et al, 1966; Daly, 1966) is among many of the most suitable finite difference schemes to simulate extensive deformation of salt and overburden. The finite difference method is relatively fast. However, the finite difference method is hard to adapt to the irregular boundaries.

The finite element method (Hirt et al, 1972; Gartling and Becker, 1976; Woidt, 1978) is also used in simulating salt diapirs. The "marker and cell" method is also implemented using finite elements (e.g. Ramaswamy, 1989). I think that the finite element implementation of the marker and cell method is best suited for the simulation of the proposed model of the evolution of salt structures in the study area, because it can handle extensive deformation and irregular boundaries.
Another numerical method called "lattice gases" is used to simulate multi-phase fluid flow and development of salt diapirs and canopies (e.g. Rothman, 1988; Gunstensen and Rothman, 1991). This method is new and requires large amounts of calculations.

Although these numerical methods have successfully simulated salt diapirs, it is obvious that the basic assumption for these numerical method still is that a salt-sediment system is represented by a fluid system that may not be realistic. Due to the presence of growth faults and to reverse faults in the salt province, we know that the overburden cannot be fully represented by a viscous fluid. Recently, some papers are published that simulate faulting associated with salt deformation (Julien et al, 1990; Chedmail et al, 1991) using the finite element method in following the analog experiments of Vendeville (1987). This method may produce realistic results close to the proposed model (Figure 14-2) for the area.

14.2.3. Ideal modeling experiments and critical phenomena to be modeled

Ideally, we would like to design a physical or numerical experiment that depicts the tectonic history of the continental slope of the northeastern Gulf of Mexico from the deposition of salt to the present. Realistically, no experiments could accomplish this for the very simple reason that no experiments are likely to completely represent nature itself. Thus if we want to better understand the constraints that best represent the geology of the northeastern Gulf of Mexico, we need to simplify what we think of the geologic evolution of the area. We ought to start modeling the geology with a working model similar to the one proposed in Figure 14-2, which in my view best summarizes the structural styles and geologic history of the northeastern Gulf of Mexico.

Assuming Figure 14-2 as a working model, some critical conditions must be met.

1) The geometry of the basement must be scaled and simplified from Map 2. The basement must also subside throughout its history according to approximated thermal
subsidence and regional isostatic adjustments under the combined sediment and salt loads through time.

2) The distribution of mid-Jurassic salt should be similar to what is shown on Map 2 with landward and seaward edges on the basement. These are critical in forming structures such as peripheral faults and The Mississippi Fan Fold Belt. Any material that represents salt should be properly scaled.

3) Pre-mid-Cretaceous sedimentation should be simulated with a large carbonate platform around and relatively thinner sediments on the slope and in the basin. Modeling of pre-mid-Cretaceous sedimentation should result in a sediment isopach similar to that documented on Map 4. The salt rollers must be produced on shelf and turtle structures, pseudo-clinoforms and deformed autochthonous salt structures and occasional allochthonous salt near the platform margin should be simulated. The mechanical properties of platform and slope carbonates and time equivalent deep-water sediments should be scaled properly.

4) A period of starved sedimentation should be simulated although the geochemical changes related to this non-deposition period will be hard to quantify. The mechanical properties of the uncovered slope carbonates and shallow salt might have been affected by extended exposure to sea water. The salt structures formed in 3) should remain stable.

5) A period of rapid clastic sediment influx of Lower-Middle Miocene should be simulated in the model. A successful model should produce the growing salt structures and the related contractional fold belt, i.e. the Mississippi Fan Fold Belt. The relationship of salt, extensional, and contractional structures must be closely studied to understand the mechanism of the formation of the fold belt. Also the growth of salt structures should be analyzed to see if active diapirism actually occurs.
6) Most important, slope conditions must be maintained throughout the experiments. The slope is essential for the formation of allochthonous salt tongues and the downslope transmission of lateral displacement related to active diapirism.

7) Varying rates of sedimentation should be modeled. Thus a successful model should replicate cessation of folding in the Mississippi Fan Belt when the allochthonous salt begins to form.

8) Continued sedimentation should produce tertiary welds and also reproduce secondary allochthonous salt sheets.

If we can model these already simplified geologic events, it would be a great success for any modeling technique. I expect that this may take some time. What can be done using available modeling techniques is to model selected critical processes, such as the lateral displacement of brittle overburden by active diapiric salt structures on a slope, the concentration of shortening on a frictional boundary, the deformation of salt under differential loading, the spreading of salt on a slope within sediments, formation of salt withdrawal basins and related extensional fault systems, etc. If the critical processes suggested in the working model are reproduced, then we will really have improved our understanding of the tectonic history of the northeastern Gulf of Mexico.
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Appendix I - Glossary for Salt Tectonics

This glossary is largely derived from Jackson and Talbot (1991). Only a few new terms are added based on this study.

**active diapirism** (syn. upbuilding, active piercement)

Post-depositional diapiric growth through prekinematic overburden. As the diapir increases in relief by growing upward, its base remains at a constant depth below the sedimentary surface, and its crest rises toward the sedimentary surface. (Vendeville and Jackson, 1992a)

**active piercement** (see active diapirism)

**allochthonous salt**

Sheetlike salt bodies emplaced at stratigraphic levels above the autochthonous source layer. Allochthonous salt lies on stratigraphically younger strata. (Jackson and Talbot, 1991)

Typical allochthonous salt structures are defined as follows.

**salt canopy**

Composite diapiric structure formed by partial or complete coalescence of diapir bulb or salt sheet. (Jackson and others, 1987)

**salt sheet**

Allochthonous salt whose breadth is several times greater than its maximum thickness; a broad, nongenetic term that includes salt tongue, etc. (Jackson and Talbot, 1991)

**salt suture**

Junction between individual salt structures that have coalesced laterally form a salt canopy. (Jackson and Talbot, 1991)
salt tongue

Highly asymmetric variety of salt sheet fed by a single stem. (Jackson and Talbot, 1991)

primary allochthonous salt

First generation allochthonous salt bodies evolved from autochthonous salt.

secondary allochthonous salt

Second generation allochthonous salt bodies evolved from primary allochthonous salt.

supra-allochthonous salt structure

Salt structures of various forms evolved from primary and secondary allochthonous salt.

autochthonous salt

Salt body resting on the original strata or surface on which it accumulated by evaporation. (Jackson and Talbot, 1991)

Typical autochthonous salt structures are defined as follows.

dynamic bulge

Bulge caused by pressure of fluid flowing against an overburden. (Jackson and Talbot, 1991)

salt anticline (syn. salt welt)

Elongated upwelling of salt having concordant overburden. (DeGolyer, 1925)

salt welt (see salt anticline)

salt diapir

Mass of salt that has flowed ductilely and appears to have discordantly pierced or intruded the overburden. (Jackson and Talbot, 1991)
salt dome

General term for a domal upwelling comprising a salt core and its envelope of deformed overburden. The salt may or may not be discordant. (Jackson and Talbot, 1991)

salt feeder

Salt walls or stocks that connect the allochthonous salt tongues or sheets with the mother salt.

salt massif

Large volume of concentrated autochthonous salt.

salt pillow

Subcircular upwelling of salt having concordant overburden. (Trusheim, 1960)

salt ridge

General term for ridge like feature formed by deformed salt.

salt roller

Low-amplitude, asymmetric salt structure comprising two flanks: a gently dipping flank in conformable stratigraphic contact with the overburden and a more steeply dipping flank in normal-faulted contact with the overburden.

salt wall

Elongated upwelling of diapiric (discordant) salt, commonly forming sinuous, parallel rows. (Trusheim, 1960)

buoyancy

Instability caused by the tendency of an overburden to sink into a less dense source layer. Buoyancy is driven by lateral pressure gradients caused by structural relief in the upper surface of the salt source layer. (Jackson and Talbot, 1991)
**decoupling level**

The zone or surface that separates two sets of strata that have differential displacement.

**density inversion**

Superposition of a dense layer above a less dense layer. (Jackson and Talbot, 1991)

**differential loading**

Creation of lateral pressure gradients on salt caused by lateral variations in thickness, density, or strength of the overburden. Such variations may be sedimentary or structural. (Jackson and Talbot, 1991)

**downbuilding** (see passive diapirism)

**gravity gliding** (syn. gravity sliding)

Downslope sliding of an overburden sheet or block under its own weight over a weak, ductile décollement such as salt or over-pressured shale. (Jackson and Talbot, 1991)

**gravity sliding** (see gravity gliding)

**gravity spreading**

Vertical collapse and lateral spreading of salt and any overburden under their own weight. (Jackson and Talbot, 1991)

**growth structure**

Local thinning of strata above and around relatively rising salt structures.

**half-turtle structure** (syn. half-turtle structure)

An analogous mound flanked by a single diapir. (Jackson and Talbot, 1991)

**mother salt** (see source layer).

**overburden**

Strata younger than the salt substratum or source layer. (Jackson and Talbot, 1991)
overburden displacement

The breaking and lateral displacement of brittle overburden by actively piercing diapiric walls or stocks.

passive diapirism (syn. downbuilding)

Syndepositional diapiric growth: the diapir increases relief by growing downward relative to the sedimentary surface. Its base subsides, together with surrounding strata, as the basin fills with sediment. The roof of diapir remains thin. (Vendeville and Jackson, 1992a)

peripheral fault

Normal fault trend around the landward limit of the mid-Jurassic Louann salt basins. (e.g. Martin, 1978)

pseudo-clinoforms

The stratal patterns that are similar to sedimentary clinoforms but formed by sequential movement of salt away from the sedimentary source. (Wu et al, 1990b)

Rayleigh-Taylor instability

Inherent instability in a layer of viscous fluid of uniform density overlying a compositionally less dense layer. Small perturbations in the horizontal interface become amplified at a rate represented by an eigenvalue that depends on the thickness, density, and viscosity of every layer, size of initial perturbation, and time elapsed. (Jackson and Talbot, 1991)

subsalt structures

Structures overlain by allochthonous salt sheets or tongues.

source layer (syn. mother salt)

Layer supplying salt for the growth of salt structures. (Jackson and Talbot, 1991)

supra-allochthonous-salt basin (syn. secondary, tertiary withdrawal basins)

Local basin formed over the allochthonous salt by the withdrawal of salt.
supra-allochthonous-salt contraction

Contrational system formed, decoupled, and limited to the allochthonous salt.

supra-allochthonous-salt extensional system

Extensional system formed, decoupled and limited to the top of allochthonous salt.

supra-allochthonous-salt structure

Salt, extensional and contractional structures formed above the allochthonous salt and related to the deformation of allochthonous salt.

turtle structure (syn. turtle-structure anticline)

Strata mounded between salt diapirs formed by the inversion of previous intra-salt basin.

upbuilding (see active diapirism)

weld (syn. salt weld)

Surface or zone joining strata originally separated by autochthonous or allochthonous salt. The weld is a negative salt structure resulting from the complete or nearly complete removal of intervening salt. (Jackson and Talbot, 1991, Jackson and Cramez, 1989)

Various generations of weld are defined as follows.

primary weld (syn. 1st weld)

The salt weld which joins strata originally separated by mother salt. (Jackson and Talbot, 1991)

secondary weld (syn. 2nd weld)

The salt weld which joins strata originally separated by steep-sided salt diapirs, walls or salt stocks. (Jackson and Talbot, 1991)

tertiary weld (syn. 3rd weld)

The salt weld which joins strata originally separated by allochthonous salt sheets. (Jackson and Talbot, 1991)
quaternary weld (syn. 4th weld)

The salt weld which joins the strata separated by steep-sided salt diapirs, walls or stocks above primary allochthonous salt.

quintic weld (syn. 5th weld)

The salt weld which joins the strata separated by secondary allochthonous salt.

1st weld (see primary weld)

2nd weld (see secondary weld)

3rd weld (see tertiary weld)

4th weld (see quaternary weld)

5th weld (see quintic weld)

withdrawal basin

Local basin accommodated by the withdrawal of salt.

Various generation of withdrawal basins are defined as follows.

primary withdrawal basin

Local basin accommodated by the withdrawal of mother salt.

secondary withdrawal basin

Local basin accommodated by the withdrawal of primary allochthonous salt.

tertiary withdrawal basin

Local basin accommodated by the withdrawal of secondary allochthonous salt.
Figure 1-5a: terminology the definition

Figure 1-5b: for velociti seaward.
Figure 1-5a. A regional NE-SW trending seismic line drawing in time. Terminology for some of the structures in the study area is introduced. See Appendix for the definition of the terms.

Figure 1-5b. Regional NE-SW trending depth converted drawing of 1-5a. See Table T1 for velocities used for depth conversion. Note that the base of mother salt dips very seaward.
Figure 1-6a. A regional NW view showing a series of structures including Supra Allochthonous Extension, Tertiary Weld, and Secondary Withdrawal B. The diagram also highlights Pseudo-Cliniforms and Secondary Weld. For some of the structures in the region, it is important to note the terms and their implications.

Figure 1-6b. Regional NW - T time line showing a depth profile with velocities used for depth conversion. The profile extends from the northern edge (NW) to the southern edge of the region.
Figure 1-6a. A regional NW - SE trending seismic line drawing in time. The terminology for some of the structures in the study area is introduced. See Appendix I for the definition of the terms.

Figure 1-6b. Regional NW - SE trending depth converted drawing of 1-6a. See Table 1-1 for velocities used for depth conversion. Note that the Mississippi Fan Fold Belt is limited to the southern edge of the mid-Jurassic salt basin.
Regional NW - SE trending seismic line drawing in time. The terminology structures in the study area is introduced. See Appendix I for the definition

Regional NW - SE trending depth converted drawing of 1-6a. See Table 1-1 and for depth conversion. Note that the Mississippi Fan Fold Belt is limited edge of the mid-Jurassic salt basin.
Figure 2-3. Two line drawings of regional seismic data from Alabama (after Wu, Vail and Cramez, 1990). See Plate IX for the correlation of sequence stratigraphic units. The sequence boundaries and maximum flooding surfaces provide a stratigraphic framework for this study on the shelf. Pleistocene sequences are correlated in the slope and basin. Note on Line B that the since 30 Ma, the sedimentary basin is in the active phase. Both Line A and B show that the normal faults on the shelf margin end of Jurassic. Significant thickness increases and the presence of primary weld show the basinward migration of normal fault at the shelf margin on Line B and the Mississippi and Alabama Shelf and Florida Terr. Jurassic. The salt-related deformation then shifted to the mostly salt with a thin layer of Norphlet sand on top.
Figure 2-3. Two line drawings of regional seismic profiles from offshore Mississippi and Alabama (after Wu, Vail and Cramez, 1990). See Figure 2-1 or inset for location. See Plate IX for the correlation of sequence stratigraphic surfaces with standard stratigraphy. The sequence boundaries and maximum flooding surfaces on Line A and B show the basic stratigraphic framework of this study on the shelf. More Middle Miocene and Plio-Pleistocene sequences are correlated in the slope area. Note that the sequences between 91.5 Ma (Turonian) and 30 Ma (mid-Oligocene) are very condensed on the slope. Also note on Line B that the since 30 Ma, the sedimentation increased rapidly.

Both Line A and B show that the normal faults on the platform ceased to develop before the end of Jurassic. Significant thickness increases of late Jurassic near the shelf margin and the presence of primary weld show the basinward withdrawal of salt. Except for one normal fault at the shelf margin on Line B and the Destin Dome (Figure 1-5), most of the Mississippi and Alabama Shelf and Florida Terrace was structurally stable since late Jurassic. The salt-related deformation then shifted to the slope area. The shaded area is mostly salt with a thin layer of Norphlet sand on top.
TRANSECT I
MESOZOIC - CENOZOIC REGIONAL
SEQUENCE STRATIGRAPHIC CORRELATION

DESTIN DOME
MISSISSIPPI SOUND-MISSISSIPPI CANYON
NORTHEASTERN GULF OF MEXICO
Figure 2-4. Regional well-log Transect I (after Wu, 1989. See Figure 2-2 for location). See Plate IX for the correlation of sequence stratigraphic surfaces with standard stratigraphy. Shown on the well-log transect across the platform and slope is the key stratigraphic information for this study. These sequence boundaries and flooding surfaces are correlated with seismic data using check-shot velocities and synthetic seismograms.
Figure 2-5. Regional well-log Transect II. SE IX for the correlation of sequence stratigraphic transect shows part of the stratigraphic continuity-Miocene-Pleistocene sequences on the slop.
well-log Transect II. See Figure 2-2 or inset for location. See Plate
of sequence stratigraphic surfaces with standard stratigraphy. This
is the stratigraphic control of the Louisiana shelf and slope for the
four sequences on the slope.
Figure 2-8a. An uninterpreted and pseudo-clinoforms. See
Figure 8a. An uninterpreted well-tie seismic section with Mid-Cretaceous allochthonous salt diapirs-clinoforms. See Figure 2-1 for location of seismic line.
Figure 2-8b. An interpreted well-tie seismic section in Figure 2-8a. See Figure 2-seismic line and Figure 2-2 for well location. An extensive primary weld fo Cretaceous strata were affected by salt withdrawal and pseudo-clinoforms former mid-Cretaceous allochthonous salt was reactivated during Late Miocene as show faults. The correlated stratigraphic surfaces are BS-base of salt (158.5 Ma) or sa
See Figure 2-1 for location of five primary weld formed. Pre-mid-clinoforms formed as shown. The Miocene as shown by the normal salt (158.5 Ma) or salt free basement (? Ma); TS-Top of Salt (150.5 Ma); MCFS-Mid-Cretaceous Flooding Surface equivalent (91.5 Ma); MO-Mid-Oligocene (30 Ma); LM-Lower Miocene (15.5 Ma); Middle Miocene (13.8 Ma); MM2-Middle Middle Miocene (12.5 Ma); MM-Middle Miocene (10.5 Ma); UM-Upper Miocene (5.5 Ma) and PLI-Pliocene (1.9 Ma). The salt.
FS-Mid-Cretaceous Flooding Surface or deep water (30 Ma); LM-Lower Miocene (15.5 Ma); MM1-Early Middle Miocene (12.5 Ma); MM3-Late Middle Miocene (15.5 Ma) and PLI-Pliocene (1.9 Ma). The shaded area is
Figure 3-5a. An uninterpreted seismic boundary. See Figure 3-4 for location of
The base of salt to salt free basement
Figure 3-5b. An interpreted seismic example of base of salt to salt free basement boundary. See Figure 3-4 for location of seismic line. This section is about four times vertically exaggerated. Note that there is a flexure near the base of basinward limit of the mid-Jurassic salt. There is no major fault cuts across the base of mid-Jurassic salt. The present Mississippi Fan is well shown by the sea floor geometry. Various erosional surfaces within the Plio-Pleistocene Mississippi Fan are not marked. The correlated
Sample of base of salt to salt free basement on seismic line. This section is about four times the flexure near the base of basinward limit of the cuts across the base of mid-Jurassic salt. The sea floor geometry. Various erosional Mississippi Fan are not marked. The correlated stratigraphic surfaces are BS-base of salt (158.5 Ma) or salt free basement. Top of Salt (150.5 Ma); LCX-a time surface in Lower Cretaceous with a MCFS-Mid-Cretaceous Flooding Surface or deep water equivalent (91.5 Ma); Oligocene (30 Ma); LM-Lower Miocene (15.5 Ma); MM1-Early Middle Miocene (12.5 Ma); MM2-Middle Middle Miocene (12.5 Ma); MM3-Late Middle Miocene (15.5 Ma); UM-Upper Miocene (5.5 Ma) and PLI-Pliocene (1.9 Ma). The shaded are
Geologic surfaces are BS-base of salt (158.5 Ma) or salt free basement (? Ma); TS-Broada (150.5 Ma); LCX-a time surface in Lower Cretaceous with undetermined age; TO-Cretaceous Flooding Surface or deep water equivalent (91.5 Ma); MO-Middle Miocene (13.8 Ma); LM-Lower Miocene (15.5 Ma); MM1-Early Middle Miocene (13.8 Ma); MM2-Middle Middle Miocene (12.5 Ma); MM3-Late Middle Miocene (10.5 Ma); MM4-Miocene (5.5 Ma) and PLI-Pliocene (1.9 Ma). The shaded area is salt.
Figure 4-3a. An uninterpreted NW - SE seismic example of a primary withdrawal basin. See Figure 4-1 for location of seismic line.
withdrawal basin.
Figure 4-3b. An interpreted NW-SE seismic example of primary formation by salt withdrawal from original salt bed. See Figure 4-1 for line. A primary withdrawal basin formed when salt withdrew from a dome. Pseudo-clinoforms, turtle structures and tension faults are also present. The synsedimentary sediments deformed in a ductile manner as in faults near the primary withdrawal basin. The correlated stratigraphic
Example of primary withdrawal basin seen in Figure 4-4. Location of seismic cross section faults are also illustrated. Note location of salt. Base of salt (158.5 Ma) or salt free basement (7 Ma). TS-Top of Salt (150 Ma). MCPS-Mid-Cretaceous Pooling Surface or deep water equivalent (91.5 Ma); MCF-Middle Cretaceous (155.5 Ma); MM2-Middle Miocene (125 Ma); MM1-Late Miocene (115 Ma); MM3-Late Miocene (105 Ma). The shaded area is salt.
Figure 4-4a. An unin
original salt bed. See 1
Figure 4-4a. An uninterpreted NW - SE seismic example of salt withdrawal from the original salt bed. See Figure 4-1 for location of seismic line.
Seismic example of salt withdrawal from the center of seismic line.
Figure 4-4b. An interpreted NW-SE seismic example of salt withdrawal from original salt bed. See Figure 4-1 for location of seismic line. Note the thickness contrast within MCFS interval. The thickness difference reflects the relative thickness of underlying strata during mid-Cretaceous-mid-Oligocene before the salt withdrew to form allochthonous salt. The correlated stratigraphic surfaces are BS-base of salt (158.5
TIE FIGURE 4-3b

Sample of salt withdrawal from original...
Note the thickness contrast within TS...
the relative thickness of underlying salt...
the salt withdrew to form the...
faces are BS-base of salt (158.5 Ma)...
or salt free basement (? Ma); TS-Top of Salt (150.5 Ma); MCFS-Mid-Cretaceous Flooding Surface or deep water equivalent (91.5 Ma); MO-Mid-Oligocene (30 Ma); LM-Lower Miocene (15.5 Ma); MM1-Early Middle Miocene (13.8 Ma); MM2-Middle Miocene (12.5 Ma); MM3-Late Middle Miocene (10.5 Ma); UM-Upper Miocene (5.5 Ma) and PLI-Pliocene (1.9 Ma). The shaded area is salt.
Pre-Salt (7 Ma); TS-Top of Salt (150.5 Ma); MCFS-Mid-Cretaceous or deep water equivalent (91.5 Ma); MO-Mid-Oligocene (30 Ma); LoO-Leonian (15.5 Ma); MM1-Early Middle Miocene (13.8 Ma); MM2-Middle Miocene (12.5 Ma); MM3-Late Middle Miocene (10.5 Ma); UM-Upper Miocene (1.9 Ma). The shaded area is salt.
Figure 4-5a. An uninterpreted NW - SE seismic exam withdrawal from original salt bed. See Figure 4-1 for l
A seismic example of normal faults related to salt. See figure 4-1 for location of seismic line.
Figure 4-5b. An interpreted NW-SE seismic example of normal faults related to salt withdrawal from original salt bed. See Figure 4-1 for location of seismic line. Pseudocliniforms, a primary weld, growth faults and tension faults were formed as a consequence of salt movements. The correlated stratigraphic surfaces are BS-base of salt (158.5 Ma) or salt free basement (? Ma); TS-Top of Salt (150.5 Ma); MCFS-Mid-

Cretaceous (30 Ma); MM2-Middle Miocene (20 Ma); Upper L
Tension Faults

Cretaceous Flooding Surface or deep water equivalent (91.5 Ma); MO-Mid-Oligocene (30 Ma); LM-Lower Miocene (15.5 Ma); MM1-Early Middle Miocene (13.8 Ma); MM2-Middle Middle Miocene (12.5 Ma); MM3-Late Middle Miocene (10.5 Ma); UM-Upper Miocene (5.5 Ma) and PLI-Pliocene (1.9 Ma). The shaded area is salt.
Figure 6-2a. An uninterpreted NW - SE seismic example of an associated growth faults. See Figure 6-1 for location of seismic lin
SE seismic example of an allochthonous salt sheet and -1 for location of seismic line.
Figure 6-2b. An interpreted NW-SE seismic section showing associated growth faults. See Figure 6-1 for detail. An allochthonous salt sheet with its undeformed tip is present. A large extensional down-to-the-basin syncline with the largest extension occurred during Late Miocene time. Extension is observed on the mid-Oligocene (M...
2b. An interpreted NW-SE seismic example of an allochthonous salt sheet and growth faults. See Figure 6-1 for location of seismic line. Note the primary salt sheet with its undeformed top. Both flat primary and steep secondary welds large extensional down-to-the basin system exists landward to the salt sheet. Note that extension occurred during Late Miocene and Pliocene (UM-PLI). Nearly 15 km of is observed on the mid-Oligocene (MO, 30 Ma) surface. The correlated stratigraphic surfaces are BS-base of salt (158 MCFS-Mid-Cretaceous Floodir Oligocene (30 Ma); LM-Lower MM2-Middle Miocene Miocene (5.5 Ma) and PLI-Plioc
Correlated stratigraphic surfaces are BS-base of salt (158.5 Ma) or salt free basement (? Ma); TS-Top of Salt (150.5 Ma); MCFS-Mid-Cretaceous Flooding Surface or deep water equivalent (91.5 Ma); MO-Mid-Oligocene (30 Ma); LM-Lower Miocene (15.5 Ma); MM1-Early Middle Miocene (13.8 Ma); MM2-Middle Middle Miocene (12.5 Ma); MM3-Late Middle Miocene (10.5 Ma); UM-Upper Miocene (5.5 Ma) and PLI-Pliocene (1.9 Ma). The shaded area is salt.
Figure 6-3a. The seismic line.
Figure 6-3a. The southward extension of Figure 6-2a. See Figure 6-1 for location of seismic line.
6-2a. See Figure 6-1 for location of
Figure 6-3b. The southward extension of Figure 6-2b. See Figure 6-1 for location of seismic line. The Mississippi Fan Fold Belt is shown. Shortening is focused near basinward limit of mid-Jurassic salt. The shortening within the fold belt ceased by the end of Late Miocene in the eastern part of the Mississippi Fan Fold Belt. The top o
Mississippi Fan Fold Belt was eroded. Less than 2 km of shor Basement is not involved in the fold belt. The fold belt has salt core salt diapir from the core of the fold belt. No shortening developed limit of mid-Jurassic salt basin.
The fold Belt was eroded. Less than 2 km of shortening are observed. No core involved in the fold belt. The fold belt has salt cores as indicated by the core of the fold belt. No shortening developed across the basinward salt basin.
Figure 6-4a. An uninterpreted NW - SE section showing associated salt withdrawal structures. See Figure 6-4b for interpretation.
Figure 6-4a. An uninterpreted NW - SE seismic example of allochthonous salt sheet and associated salt withdrawal structures. See Figure 6-1 for location of seismic line.
Seismic example of allochthonous salt sheet and Figure 6-1 for location of seismic line.
Figure 6-4b. An interpreted NE-SW seismic example of allochthonous salt sheet and associated salt withdrawal structures. See Figure 6-1 for location of seismic line. Primary and secondary welds, an allochthonous salt sheet, a turtle structure which was developed from an inverted primary withdrawal basin, and tension faults are well imaged on this seismic example. The correlated stratigraphic surfaces are BS-base of salt (158.5 Ma) or
NE-SW seismic example of allochthonous salt sheet and structures. See Figure 6-1 for location of seismic line. Primary allochthonous salt sheet, a turtle structure which was developed in a withdrawal basin, and tension faults are well imaged on this seismic. Stratigraphic surfaces are BS-base of salt (158.5 Ma) or salt free basement (? Ma); TS-Top of Salt (150.5 Ma); MC1 Surface or deep water equivalent (91.5 Ma); MO-Mid-Oligocene (15.5 Ma); MM1-Early Middle Miocene (13.8 Ma); MM2-Late Middle Miocene (12.5 Ma); MM3-Late Middle Miocene (10.5 Ma) and PLI-Pliocene (1.9 Ma). The shaded area is salt.
Primary Allochthonous Salt Sheet

Basement (? Ma); TS-Top of Salt (150.5 Ma); MCFS-Mid-Cretaceous Flooding Surface or deep water equivalent (91.5 Ma); MO-Mid-Oligocene (30 Ma); LM-Lower Miocene (15.5 Ma); MM1-Early Middle Miocene (13.8 Ma); MM2-Middle Middle Miocene (12.5 Ma); MM3-Late Middle Miocene (10.5 Ma); UM-Upper Miocene (5.5 Ma); and PL1-Pliocene (1.9 Ma). The shaded area is salt.
Figure 6-5a. An uninterpreted NE-SW allochthonous salt sheet. See Figure 6-1 for loca...
Figure 6-5a. An uninterpreted NE-SW seismic example of a well imaged lachthonous salt sheet. See Figure 6-1 for location of seismic line.
example of a well imaged seismic line.
Figure 6-5b. An interpreted NE-SW seismic example of a well imaged allochthonous salt sheet. See Figure 6-1 for location of seismic line. Note that top of the salt sheet is relatively undeformed although it is under about 1 km of sediment load. The correlated stratigraphic surfaces are BS-base of salt (158.5 Ma) or salt free basement (? Ma); TS-
SW seismic example of a well imaged allochthonous section of seismic line. Note that top of the salt sheet is under about 1 km of sediment load. The correlated Top of Salt (150.5 Ma); MO-Mid-Oligocene (30 Ma); LM-Lowe MM1-Early Middle Miocene (13.8 Ma); MM2-Middle Middle MM3-Late Middle Miocene (10.5 Ma); UM-Upper Miocene (5.5 (1.9 Ma). The shaded area is salt.
(150.5 Ma); MO-Mid-Oligocene (30 Ma); LM-Lower Miocene (15.5 Ma);
Middle Miocene (13.8 Ma); MM2-Middle Middle Miocene (12.5 Ma);
Middle Miocene (10.5 Ma); UM-Upper Miocene (5.5 Ma) and PLI-Pliocene
the shaded area is salt.
Figure 6-7a. An uninterpreted NW withdrawal basins on primary and secondary 1 for location of seismic line.
Figure 6-7a. An uninterpreted NW - SE seismic example of secondary and tertiary withdrawal basins on primary and secondary allochthonous salt respectively. See Figure 6-7c for location of seismic line.
of secondary and tertiary respectively. See Figure 6-
Figure 6-7b. An interpreted NW-SE seismic example of secondary and tertiary withdrawal basins on primary and secondary allochthonous salt respectively. See Fig 6-1 for location of seismic line. Note that extension in the secondary and tertiary withdrawal basins is accommodated by the deformation of primary and secondary allochthonous salt. Note also that a bathymetric relief is formed over the undeform
Seismic example of secondary and tertiary allochthonous salt respectively. See Figure that extension in the secondary and tertiary deformation of primary and secondary geometric relief is formed over the undeformed secondary allochthonous salt. Rapid sedimentation and salt deformation Pleistocene is also observed in this example. The correlated stratigraphic sections PL1-Pliocene (1.9 Ma), P1-P5-Undifferentiated Pleistocene reflectors. The show salt.
allochthonous salt. Rapid sedimentation and salt deformation during observed in this example. The correlated stratigraphic surfaces are (Ma), P1-P5-Undifferentiated Pleistocene reflectors. The shaded area is
Figure 7-2a. An uninterpreted NW-SE seismic example from the ea Mississippi Fan Fold Belt. See Figure 7-1 for location of seismic line.
A seismic example from the eastern part of a seismic line.
Figure 7-2b. An interpreted NW - SE seismic Fan Fold Belt. See Figure 7-1 for location of thickness, the shortening occurred during M limited to the basinward limit of the mid-Jur eroded. A salt tongue developed from the shortening ceased to be active. The active tong Note that thick autochthonous salt is in the converge to the south. The calculations from a
7-2b. An interpreted NW - SE seismic example from the eastern part of Mississippi fold Belt. See Figure 7-1 for location of seismic line. As shown by the convergence of thrusts, the shortening occurred during MM1 (13.8 Ma) - UM (5.5). The shortening is limited to the basinward limit of the mid-Jurassic salt basin. The top of the fold belt was raised. A salt tongue developed from the salt core of the fold belt despite that the shortening ceased to be active. The active tongue forms a dynamic bulge on the sea floor. It is apparent that thick autochthonous salt is in the core of the fold belt. Most of the reverse faults are to the south. The calculations from a depth section (not illustrated) show that the shortening in this part of the fold belt is significant. The correlated stratigraphic sections indicate a free basement (? Ma); TS-Top of Surface or deep-water equivalent (9.5 Ma); MM1-Early Miocene (15.5 Ma); MM2-Late Miocene (12.5 Ma); MM3-Late Miocene (6 Ma) and PLI-Pliocene (1.9 Ma). The
The convergence of shortening in this part of the fold belt is about 1.75 km (2.8% of total deformed length of the fold belt). The correlated stratigraphic surfaces are BS-base of salt (158.5 Ma) or salt-free basement (? Ma); TS-Top of Salt (150.5 Ma); MCFS-Mid-Cretaceous Flooding Surface or deep-water equivalent (91.5 Ma); MO-Mid-Oligocene (30 Ma); LM-Lower Miocene (15.5 Ma); MM1-Early Middle Miocene (13.8 Ma); MM2-Middle Miocene (12.5 Ma); MM3-Late Middle Miocene (10.5 Ma); UM-Upper Miocene (5.5 Ma) and PLI-Pliocene (1.9 Ma). The shaded area is salt.
Figure 7-4a. An uninterpreted NW - SE seismic example of doubly verg from the middle part of the Mississippi Fan Fold Belt. See Figure 7-seismic line.
SE seismic example of doubly vergent reverse faults in the Mississippi Fan Fold Belt. See Figure 7-1 for location of...
Figure 7-4b. An interpreted NW - SE seismic example of doubly vergent reverse faults from the middle part of the Mississippi Fan Fold Belt. See Figure 7-1 for location of seismic line. Note that the fold belt has thick salt cores which form typical salt anticline (Jackson and Talbot, 1991) or salt welt (Harrison and Bally, 1988). The correlated stratigraphic surfaces are BS-base of salt (158.5 Ma) or salt-free basement (? Ma); TS-
Top of Salt (150 Ma); MM1-Early Middle Miocene (10 Ma); MM3-Late Middle Miocene (1.9 Ma). The shade
These faults are an indication of a downthrown anticline.
Top of Salt (150.5 Ma); MCFS-Mid-Cretaceous Flooding Surface or deep-water equivalent (91.5 Ma); MO-Mid-Oligocene (30 Ma); LM-Lower Miocene (15.5 Ma); MM1-Early Middle Miocene (13.8 Ma); MM2-Middle Middle Miocene (12.5 Ma); MM3-Late Middle Miocene (10.5 Ma); UM-Upper Miocene (5.5 Ma) and PLI-Pliocene (1.9 Ma). The shaded area is salt.
Figure 7-6a. An uninterpreted faults from the western end of seismic line.
Figure 7-6a. An uninterpreted NW - SE seismic example of landward verging reverse faults from the western end of the Mississippi Fan Fold Belt. See Figure 7-1 for location of seismic line.
Profile of landward verging reverse fault. See Figure 7-1 for location.
Figure 7-6b. An interpreted NW - SE seismic example of landward verging from the western end of the Mississippi Fan Fold Belt. See Figure 7-1 for seismic line. Note that as shown by the convergence of thickness, the southwestern part of the Mississippi Fan Fold Belt occurred during LM (15.5 Ma) Ma). Top of the fold belt is also eroded. The fold belt ceased to be active although sedimentation increased greatly since then as the Mississippi Fan wa
The correlated stratigraphic surfaces are BS-base (7 Ma); TS-Top of Salt (150.5 Ma); MCFS-Mid-water equivalent (91.5 Ma); MO-Mid-Oligocene (Ma); MM1-Early Middle Miocene (13.8 Ma); MM2-Middle Miocene (10.5 Ma); UM-Upper Miocene (1.9 Ma). The shaded area is salt.
Correlated stratigraphic surfaces are BS-base of salt (158.5 Ma) or salt-free basement (Ma); TS-Top of Salt (150.5 Ma); MCFS-Mid-Cretaceous Flooding Surface or deep-equivalent (91.5 Ma); MO-Mid-Oligocene (30 Ma); LM-Lower Miocene (15.5 Ma); MM1-Early Middle Miocene (13.8 Ma); MM2-Middle Middle Miocene (12.5 Ma); LM1-Late Middle Miocene (10.5 Ma); UM-Upper Miocene (5.5 Ma) and PLI-Pliocene (Ma). The shaded area is salt.
Figure 7-9a. An uninterpreted NW-SE seismic example and its associated growth faults. See Figure 7-1 for locati
NW - SE seismic example of an allochthonous salt sheet. See Figure 7-1 for location of seismic line.
Figure 7-9b. An interpreted NW - SE seismic example of an allochthonous salt sheet and its associated growth faults. See Figure 7-1 for location of seismic line. Note the large allochthonous salt sheet and the primary withdrawal basin behind the salt sheet. The allochthonous salt began to develop after massive salt diapirism during Middle Miocene (MM1-MM3) as shown by the convergence of the Middle Miocene interval toward the master.
Location on the master-down-to-the-basin Miocene well after the formation of the Miocene. The extension of the MO near the roll-over associated with the surfaces are BS-base of salt (158.5 Ma) or salt free basement (? Ma); TS-Top of Salt (150.5 Ma); MCFS-Mid-Cretaceous Flooding Surface or deep water equivalent (91.5 Ma); MO-Mid-Oligocene (30 Ma); LM-Lower Miocene (15.5 Ma); MM1-Early Middle Miocene (13.8 Ma); MM2-Middle Miocene (12.5 Ma); MM3-Late Middle Miocene (10.5 Ma); UM-Upper Miocene (5.5 Ma) and PLI-Pliocene (1.9 Ma). The shaded area is salt.
LC-15 (150.5 Ma); MCFS-Mid-Cretaceous (150.5 Ma); MO-Mid-Oligocene (30 Ma); MM-Middle Miocene (13.8 Ma); MM2-Middle Miocene (13.8 Ma); UM-Middle Miocene (10.5 Ma); UM-Upper Miocene area is salt.
Figure 7-10a. An uninterpreted NW - SE seismi
cal of Figure 7-9a. See Figure 7-1 for locatio
Figure 7-10a. An uninterpreted NW - SE seismic example of fold and reverse faults to the south of Figure 7-9a. See Figure 7-1 for location of seismic line.
Figure 7-10b. An interpreted NW - SE seismic example of fold and reverse faults to the south of Figure 7-9b. See Figure 7-1 for location of seismic line. The shortening occurred mostly during Middle Miocene and ceased by Late Miocene although the updip extension of the master growth fault reached a maximum much later during Late Miocene and Pliocene. The shortening was coeval with the massive diapirism of salt during Middle Miocene. The shortening in the fold belt (less than 2 km) is far less that the extension in the updip master down-to-the-basin growth fault. Salt cores and the fold at the northern end of the belt. Base Mid Olig Ma
Seismic example of fold and reverse faults to the location of seismic line. The shortening occurred by Late Miocene although the updip extension maximum much later during Late Miocene and the massive diapirism of salt during Middle less than 2 km) is far less than the extension in each fault. Salt cores and the fold at the northern end continued to grow during Pliocene after the cessation of the short belt. The top of the fold belt is also eroded. The correlated stratigraphic base of salt (158.5 Ma) or salt free basement (? Ma); TS-Top of Salt (1 Mid-Cretaceous Flooding Surface or deep water equivalent (91.5 Oligocene (30 Ma); LM-Lower Miocene (15.5 Ma); MM1-Early Middle (Ma); MM2-Middle Middle Miocene (12.5 Ma); MM3-Late Middle Miocene (5.5 Ma) and PLI-Pliocene (1.9 Ma). The shaded at
during Pliocene after the cessation of the shortening in the fold belt is also eroded. The correlated stratigraphic surfaces are BS-salt free basement (? Ma); TS-Top of Salt (150.5 Ma); MCFS-salt free basement or deep water equivalent (91.5 Ma); MO-Middle-Lower Miocene (15.5 Ma); MM1-Early Middle Miocene (13.8 Ma); MM2-Lower Middle Miocene (12.5 Ma); MM3-Late Middle Miocene (10.5 Ma); MM4-Upper Middle Miocene (9.5 Ma) and PLI-Pliocene (1.9 Ma). The shaded area is salt.
Figure 10-2a. An uninterpreted NW-SE seismic example of early suprallochthonous-salt growth faults. See Figure 10-1 for location of seismic line.
Seismic example of early supra-
-1 for location of seismic line.
Figure 10-2b. An interpreted salt growth faults. See Figure withdrawal basins on top of allochthonous extensional growth compressional folds develop due to allochthonous salt. The leading sea floor. Some of the sedimen
Figure 10-2b. An interpreted NW-SE seismic example of early supra-allochthonous-salt growth faults. See Figure 10-1 for location of seismic line. Note the secondary withdrawal basins on top of the allochthonous salt sheet. Extension of the supra-allochthonous extensional growth faults is accommodated by salt withdrawal. No compressional folds develop due to the growth fault. Growth faults sole out on top of the allochthonous salt. The leading edge of the salt sheet forms the Sigsbee Escarpment on the sea floor. Some of the sediments in front of the salt sheet were thrusted and eroded. The correlated stratigraphic unit is MM1 (91.5 Ma); TS-Top of Salt equivalent (91.5 Ma); MM1-Early Middle Miocene; Late Middle Miocene (91 Ma). The shaded area represents the secondary withdrawal basin.
correlated stratigraphic surfaces are BS-base of salt (158.5 Ma) or salt free basement (? Ma); TS-Top of Salt (150.5 Ma); MCFS-Mid-Cretaceous Flooding Surface or deep water equivalent (91.5 Ma); MO-Mid-Oligocene (30 Ma); LM-Lower Miocene (15.5 Ma); MM1-Early Middle Miocene (13.8 Ma); MM2-Middle Middle Miocene (12.5 Ma); MM3-Late Middle Miocene (10.5 Ma); UM-Upper Miocene (5.5 Ma) and PLI-Pliocene (1.9 Ma). The shaded area is salt.
Primary Chthonous Salt

SIGSBEE ESCARPMENT

TWO WAY TIME IN SECONDS

Surface or deep water Miocene (15.5 Ma); Serravallian or early Miocene (12.5 Ma); MM3-Middle Miocene (10 Ma) and PLI-Pliocene (1.9 Ma)
Figure 10-3a. An uninterpreted NW-allochthonous-salt growth fault. See Fig.
Figure 10-3a. An uninterpreted NW - SE seismic example of a well developed supra-allochthonous-salt growth fault. See Figure 10-1 for location of seismic line.
A well-developed supra-
seismic line.
Figure 10-3b. An interpreted NW - SE seismic example of a well developed supra-allochthonous-salt growth fault and secondary withdrawal basin. See Figure 10-1 for location of seismic line. Note that more extension in the secondary withdrawal basin is accommodated by more allochthonous salt deformation. No compressional structure is
The seismic example of a well developed supralateral withdrawal basin. See Figure 10-1 for the extension in the secondary withdrawal basin is salt deformation. No compressional structure is formed at the toe of the extensional faults. Growth faults sole out allochthonous salt. The correlated stratigraphic surface is PLI-Pliocene shaded area is salt.
extensional faults. Growth faults sole out at the top of the related stratigraphic surface is PLI-Pliocene (1.9 Ma). The
Figure 10-4a. An uninterpreted NW - SE seismic example of allochthonous-salt growth faults and welds. See Figure 10-1 for l
interpreted NW-SE seismic example of well developed supra-reflects and welds. See Figure 10-1 for location of seismic line.
Figure 10-4b. An interpreted allochthonous-salt growth fault. See Figure 10-1 for location of accommodation by primary and develop at the toe of the extensional BS-base of salt (158.5 Ma).
Figure 10-4b. An interpreted NW-SE seismic example of well developed supra-allochthonous-salt growth faults, secondary withdrawal basins and tertiary welds. See Figure 10-1 for location of seismic line. Note that most of the extension was accommodated by primary allochthonous salt deformation. No compressional structures develop at the toe of the extensional systems. The correlated stratigraphic surfaces are BS-base of salt (158.5 Ma) or salt free basement (? Ma); TS-Top of Salt (150.5 Ma); MCFS-Mid-Cretaceous Oligocene (30 Ma); T Ma); MM2-Middle Miocene; UM—Upper Miocene; Pliocene (3.0 Ma); F area is salt.
FIGURE 10-5b

- MCFS-Mid-Cretaceous Flooding Surface or deep water equivalent (91.5 Ma); MO-Mid-Oligocene (30 Ma); LM-Lower Miocene (15.5 Ma); MM1-Early Middle Miocene (13.8 Ma); MM2-Middle Middle Miocene (12.5 Ma); MM3-Late Middle Miocene (10.5 Ma); UM-Upper Miocene (5.5 Ma); PL11-Pliocene (4.2 Ma); PL12-Pliocene (3.8 Ma); PL13-Pliocene (3.0 Ma); PL14-Pliocene (2.4 Ma) and PL15-Pliocene (1.9 Ma). The shaded area is salt.
Figure 10-6a. An uninterpreted NW - SE tertiary weld. See Figure 10-1 for location c.
Figure 10-6a. An uninterpreted 'NW - SE' seismic example of a deep and well developed tertiary weld. See Figure 10-1 for location of seismic line.
Figure 10-6b. An interpreted NW-SE seismic primary weld. See Figure 10-1 for location. Also note the lower primary weld. The Pliocene (1.9 Ma). The shaded area is salt.
Figure 10-6b. An interpreted NW - SE seismic example of a deep and well developed tertiary weld. See Figure 10-1 for location of seismic line and Figure 2-2 for well location. Also note the lower primary weld. The correlated stratigraphic surface is Pliocene (1.9 Ma). The shaded area is salt.
Example of a deep and well developed...
Figure 10-7a. An uninterpreted NW-SE seismic example of supra-a growth faults and reverse faults. See Figure 10-1 for location of seismic li
NNW - SE. Seismic example of supra-allochthonous salt.

Figure 10.1 for location of seismic line.
Figure 10-7b. An interpreted NW-SE seismic example of supra-allochthonous extensional growth faults and reverse faults. See Figure 10-1 for location of seismic Two phases of shortening occurred as shown by the convergence and truncation between PL12 and the convergence above P3. During a first phase of shortening before PL12, rose as shown by the convergence of overburden against salt and no extensional
SE seismic example of supra-allochthonous-salt faults. See Figure 10-1 for location of seismic line. The convergence and truncation below is shown by the convergence and truncation below during a first phase of shortening before PL12, salt movement on the slope is the cause of two phases of deformation. The tertiary weld is better defined on the perpendicular line in.
6. The secondary withdrawal basin fault, developed in the updip fold thickened, allochthonous salt.

Correlated stratigraphic surfaces are MM1-Early Middle Miocene (13.8 Ma), MM2-Middle Miocene (12.5 Ma), MM3-Late Middle Miocene (10.5 Ma), PL1-PLiocene (7 Ma), PL2-PLiocene (1.9 Ma), and PL3-PLiocene (0 Ma). The shaded area is salt.

The faults in Figure 10.8b have the following characteristics:

- **Fold and Reverse Fault:**
- **LANDWARD Dipping:**
- **GROWTH FAULTS:**

The diagram shows the orientation and nature of the faults, indicating the direction of movement and the structural features involved in the deformation of the basin.
Early Middle Miocene (13.8 Ma); MM2-
Middle Miocene (10.5 Ma); UM-Upper 
PLI2-Pliocene (1.9 Ma) and P1-P3-
The shaded area is salt.
Figure 10-8a. An uninterpreted NW - SE seismic perpendicular to Figure 10-6a. See Figure 10-1 for location.
NW-SE Seismic example of a tertiary weld

Figure 10.1 for location of seismic line.

COURTESY OF GECO-PRKILA

SCALE

3 MILES

5 KM

TWO WAY TIME IN SECONDS
Figure 10-8b. An interpreted NE-SW seismic example of a tertiary weld perpendicular to Figure 10-6b. See Figure 10-1 for location of seismic line. The correlated stratigraphic surfaces are MM1-Early Middle Miocene (13.8 Ma); MM2-Middle Middle Miocene (12.5 Ma); MM3-Lat Pliocene (? Ma) reflectors (? Ma).
Ma); MM3-Late Middle Miocene (10.5 Ma); UM-Upper Miocene (5.5 Ma); PLI-Pliocene (? Ma); PLI2-Pliocene (1.9 Ma) and P1-P3 Undifferentiated Pleistocene reflectors(? Ma). The shaded area is salt.
Figure 11-3a. An uninterpreted NW - SE seismic example of submarine Sigsbee Scarp and Mississippi Fan Fold Belt. See Figure 11-1 for location of se
example of submarine erosion at Figure 11-1 for location of seismic line.
Figure 11-3b. An interpreted NW Scarp and Mississippi Fan Fold correlated stratigraphic surfaces (Ma); TS-Top of Salt (150.5 Ma)
Figure 11-3b. An interpreted NW - SE seismic example of submarine erosion at Sigsbee Scarp and Mississippi Fan Fold Belt. See Figure 11-1 for location of seismic line. The correlated stratigraphic surfaces are BS-base of salt (158.5 Ma) or salt free basement (? Ma); TS-Top of Salt (150.5 Ma); MCFS-Mid-Cretaceous Flooding Surface or deep water equivalent (91.5 Ma); MM1-Early Middle Miocene; Late Middle Miocene (? Ma). The shaded area is
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PLATE I

REGIONAL LINE DRAWINGS OF NNW - SSE SEISMIC PROFILES
NORTH-EASTERN GULF OF MEXICO

INDEX MAP

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PLATE II

REGIONAL LINE DRAWINGS OF NNW - SSE SEISMIC PROFILES
NORTH-EASTERN GULF OF MEXICO

INDEX MAP

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PLATE III

REGIONAL LINE DRAWINGS OF NNW - SSE SEISMIC PROFILES
NORTH-EASTERN GULF OF MEXICO

INDEX MAP

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PLATE IV

REGIONAL LINE DRAWINGS OF...
PLATE IV

REGIONAL LINE DRAWINGS OF NNW - SSE SEISMIC PROFILES - NORTH-EASTERN GULF OF MEXICO

INDEX MAP

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PLATE V

REGIONAL LINE DRAWINGS OF NNW - SSE SEISMIC PROFILES NORTH-EASTERN GULF OF MEXICO

INDEX MAP

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PLATE VI

REGIONAL LINE DRAWINGS OF NNW - SSE SEISMIC PROFILES
NORTH-EASTERN GULF OF MEXICO

INDEX MAP
PLATE VI

REGIONAL LINE DRAWINGS OF NNW - SSE SEISMIC PROFILES
NORTH-EASTERN GULF OF MEXICO

INDEX MAP

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PLATE VII

REGIONAL LINE DRAWINGS OF SWW - NEE SEISMIC PROFILES NORTH-EASTERN GULF OF MEXICO
PLATE VII

REGIONAL LINE DRAWINGS OF
SWW - NEE SEISMIC PROFILES
NORTH-EASTERN GULF OF MEXICO

INDEX MAP

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PLATE VIII
REGIONAL LINE DRAWINGS OF SWW - NEE SEISMIC PROFILES NORTH-EASTERN GULF OF MEXICO
PLATE VIII

REGIONAL LINE DRAWINGS OF
SWW - NEE SEISMIC PROFILES
NORTH-EASTERN GULF OF MEXICO

INDEX MAP

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<th>Eastern Gulf Coast/Gulf of Mexico Groups/Formations (2)</th>
<th>Biostratigraphy (3)</th>
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</tbody>
</table>

**Notes:**
- **Eratem:** Quaternary, Pliocene, Neogene, Oligocene, Eocene.
- **System:** Pleistocene, Pliocene, Miocene, Oligocene, Eocene.
- **Series:** Lower (L), Upper (U).
- **Stages:** Zanclean, Messinian, Langhian, Burdigalian, Aquitanian, Sarnian.
- **Groups/Formations:** Citronelle Group, Fleming Group, Vicksburg Group, Claiborne Group.
- **Biostratigraphy:** GULF COAST/GULF OF MEXICO BENTHIC FORAMINIFERA.
- **Planktonic Foraminifera Zones:** N22, N20, N19, N18, N17, N16, N15, N14, N12, N11, N10, N9, N8, N7, N6, N5, N4, P22, P21, P20, P19, P18, P17, P16, P15, P14, P13, P12, P11, P10, P9, P8, P7, P6, P5, P4, P3, P2, P1.
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PLATE XI
REGIONAL SEISMIC LINE DRAWINGS
OFFSHORE NIGERIA

LEGEND
- SEA FLOOR
- L. PLIOCENE (4.2 Ma ?)
- M. MIocene (Ma ?)
- L. PALEOCENE (Ma ?)
- CRETACEOUS OCEANIC BASEMENT
- CHARCOT FRACTURE ZON
- HIGHLY DEFORMED SHALE
- FAULTS

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SEISMIC DATA:
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LEGEND

ALLOCHTHONOUS SALT

THIN ALLOCHTHONOUS SALT
(< 200 MS TWO WAY TIME)

NORMAL FAULTS ON MID-Oligocene (30 MA)
NORMAL FAULTS ON BASE OF SALT (158.5 MA)
THRUST FAULTS ON MID-Oligocene (30 MA)
IN THE MISSISSIPPI FAAN FOLDBELT

SOUTHERN DEPOSITIONAL LIMIT OF
MID-JURASSIC SALT

CONTOUR INTERVAL = .5 KILOMETERS (DEPTH).

<5 KM
5-7 KM
7-9 KM
9-11 KM
11-13 KM
> 13 KM

MAP INDEX

Seismic Coverage
(decimal map)

Texas
Louisiana
Gulf of Mexico

MAP AREA

Schematic Cross Section

Sediment 0 MA
5.0 MA
10 MA
15 MA
20 MA
25 MA
30 MA
35 MA
40 MA

Depth

MAPPED INTERVAL OR SURFACE IS INDICATED BY ARROWS.
SOUTHERN DEPOSITIONAL LIMIT OF MID-JURASSIC SALT

CONTOUR INTERVAL = .5 KILOMETERS (DEPTH)

<5 KM
5-7 KM
7-9 KM
9-11 KM
11-13 KM
> 13 KM
STRUCTURE MAP
BASE OF SALT (158.5 MA)/
SALT FREE BASEMENT (? MA)
MAP 2

AREA: NORTH-EASTERN GULF OF MEXICO

AUTHOR: SHENGYU WU
ADVISOR: ALBERT W. BALLY
SPONSORS: GECO-PRKLA, TOTAL

HOUSTON, TEXAS
APRIL 1982
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MID-JURASSIC SALT

CONTOUR INTERVAL = .6 KILOMETERS
(VERTICAL THICKNESS)

< 1 KM
1-3 KM
3-5 KM
5-7 KM
7-9 KM
> 9 KM

UNIT 25 SOIL
SWERED SOIL
60'00'
50'30'
50'00'
40'30'
40'00'
30'30'
30'00'
20'30'
20'00'
10'30'
10'00'
00'30'
00'00'

SOUTH TIMBERLIER SOUTH
GREEN CANYON
GARDEN BANKS
KEARNEY CANYON
WALKER R

MAPPED INTERVAL OR SURFACE IS INDICATED BY ARROWS.
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LEGEND

ALLOCHTHONOUS SALT

THIN ALLOCHTHONOUS SALT
(< 200 MS TWO WAY TIME)

NORMAL FAULT ON MID-OLIGOCENE (30 MA)

THRUST FAULTS ON MID-OLIGOCENE (30 MA)
IN THE MISSISSIPPI FAN FOLDBELT

SOUTHERN DEPOSITIONAL LIMIT OF
MID-JURASSIC SALT

CONTOUR INTERVAL = .5 SECONDS (T.W.T.)

.2-1 SECONDS

1-1.5 SECONDS

1.5-2 SECONDS

2-2.5 SECONDS

2.5-3 SECONDS

> 3 SECONDS

MAP INDEX

SEISMIC COVERAGE
(OECO DEEP MARIN SURVEY)

TEXAS

LOUISIANA

GULF OF MEXICO

MAP AREA

SCHEMATIC CROSS SECTION

BASE MID-J. SALT

MAPPED INTERVAL OR SURFACE IS INDICATED BY ARROWS.
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LEGEND

ALLOCHTHONOUS SALT

THIN ALLOCHTHONOUS SALT
(< 200 MS TWO WAY TIME)

NORMAL FAULT ON MID-Oligocene (30 MA)

THRUST FAULTS ON MID-Oligocene (30 MA)
IN THE MISSISSIPPI FAN FOLDBELT

SOUTHERN DEPOSITIONAL LIMIT OF
MID-JURASSIC SALT

CONTOUR INTERVAL = .5 SECONDS (T.W.T.)

< 1 SECOND

1-2 SECONDS

2-3 SECONDS

3-4 SECONDS

4-5 SECONDS

> 5 SECONDS

MAP INDEX

Gulf of Mexico

Texas

Louisiana

Seismic Coverage

(Geco Deep Margin Survey)

Map Area

Schematic Cross Section

SEA FLOOR

9 MA

13 MA

15 MA

16 MA

17 GA

Salt Free Basement

MAPPED INTERVAL OR SURFACE IS INDICATED BY ARROWS.
PLEASE NOTE:

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THRUST FAULTS ON MID-OLIGOCENE (30 MA) IN THE MISSISSIPPI FAN FOLDBELT

SOUTHERN DEPOSITIONAL LIMIT OF MID-JURASSIC SALT

CONTOUR INTERVAL = .25 SECONDS (T.W.T.)

< .5 SECONDS

.5-1.0 SECONDS

1.0-1.5 SECONDS

1.5-2.0 SECONDS

> 2.0 SECONDS
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LEGEND

ALLOCHTHONOUS SALT

THIN ALLOCHTHONOUS SALT
(< 200 MS TWO WAY TIME)

NORMAL FAULT ON 5.5 MA

LOCAL REVERSE FAULTS ON 5.5 MA

SOUTHERN DEPOSITIONAL LIMIT OF MID-JURASSIC SALT

MAP INDEX

SEISMIC COVERAGE

(TEXCO DEEP MARGIN SURVEY)

MAP AREA

Schematic Cross Section

MAPPED INTERVAL OR SURFACE IS INDICATED BY ARROWS.
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