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Seismic sequence stratigraphy of the
Lower Congo, Kwanza, and Benguela Basins,
offshore Angola, Africa

by

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A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
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ABSTRACT

Sequences are recognized throughout the geologic record. The Angolan margin provides an excellent opportunity to examine the factors that control the deposition and preservation of sediments in sequences, as well as the factors that create the erosion or non-deposition along sequence boundaries. The Angolan sequences can be compared to global sequence charts and used to investigate the effects of local events versus global events on the area's sequences.

Using seismic sequence stratigraphic principles, a 2D regional seismic data set covering three basins offshore Angola, the Lower Congo, Kwanza, and Benguela Basins, was interpreted. Sequences and their unconformities were correlated within each basin as well as between basins. Major sequences could be interpreted throughout and between the three basins with a high degree of confidence. Additional sequences within these major sequences were interpreted within a basin, but could not be correlated to the adjacent basin with a high degree of confidence. Detailed interpretation of the sequence stratigraphic significance of each reflector was performed on three profiles, one for each basin. Chronostratigraphic charts were constructed using the detailed interpretation of the profiles. Within the interpreted sequence stratigraphic framework, the timing and mechanics of the formation of salt structures was examined. The Angolan basins contain a variety of salt tectonic features. The reflectors of strata adjacent to the salt features were used to determine the timing and mechanics of the salt structure formation.
This study accomplished several objectives. The tectonic evolution of the Angolan margin was reviewed. This study established a sequence stratigraphic framework for Angola. The process of deposition and preservation of sediments as depositional sequences was examined. The sequences were compared with the global sequence charts as well as with eustatic, tectonic, and oceanic circulation events. The formation of the sequence bounding unconformities was examined. Within the sequences, the interaction of sedimentation and salt movement was described.
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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>ii</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>iv</td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td>v</td>
</tr>
<tr>
<td>LIST OF ILLUSTRATIONS</td>
<td>ix</td>
</tr>
<tr>
<td>CHAPTER 1 - INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Objectives</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Study Area</td>
<td>1</td>
</tr>
<tr>
<td>1.3 Data Set</td>
<td>3</td>
</tr>
<tr>
<td>1.4 Methodology</td>
<td>6</td>
</tr>
<tr>
<td>CHAPTER 2 - TECTONIC EVOLUTION OF THE ANGOLAN MARGIN</td>
<td>8</td>
</tr>
<tr>
<td>2.1 General evolution</td>
<td>8</td>
</tr>
<tr>
<td>2.2 Pre-rifting</td>
<td>9</td>
</tr>
<tr>
<td>2.3 Rifting</td>
<td>10</td>
</tr>
<tr>
<td>2.4 Oceanward divergent reflectors</td>
<td>20</td>
</tr>
<tr>
<td>2.5 Post rift sedimentation</td>
<td>20</td>
</tr>
<tr>
<td>2.6 Salt</td>
<td>22</td>
</tr>
<tr>
<td>2.7 Post salt units</td>
<td>24</td>
</tr>
<tr>
<td>2.8 Tertiary uplift</td>
<td>29</td>
</tr>
<tr>
<td>2.9 Seamounts</td>
<td>31</td>
</tr>
<tr>
<td>2.10 Stratigraphic columns</td>
<td>35</td>
</tr>
</tbody>
</table>
CHAPTER 3 - ANGOLAN SEQUENCE STRATIGRAPHIC FRAMEWORK......39

3.1 Angolan Basins ................................................................. 39
3.2 Major sequence 1 .............................................................. 82
3.3 Major sequence 2 .............................................................. 113
3.4 Major sequence 3 .............................................................. 143
3.5 Major sequence 4 .............................................................. 182
3.6 Lower Congo Basin seismic sequence stratigraphy .................... 218
3.7 Kwanza Basin seismic sequence stratigraphy ............................ 230
3.8 Benguela Basin seismic sequence stratigraphy ........................ 238

CHAPTER 4 - UNDERSTANDING UNCONFORMITIES .......................247

4.1 Introduction ................................................................. 247
4.2 Sea-level changes ........................................................... 247
  4.2.1 Relative Sea-Level vs. Eustasy ........................................ 247
  4.2.2 How sea-level changes create erosion and non-deposition .... 250
  4.2.3 History of sea-level .................................................... 252
  4.2.4 How unconformities formed by sea-level changes are identified 255
4.3 Tectonics ........................................................................ 258
  4.3.1 The relation of erosion and non-deposition to tectonics ...... 258
  4.3.2 Types of unconformities associated with tectonic events .... 258
  4.3.3 How are unconformities formed by tectonics identified ...... 266
4.4 Currents ......................................................................... 267
  4.4.1 History of current patterns ............................................ 267
4.4.2 How currents cause erosion and non-deposition ........................................... 273
4.4.3 Identification of unconformities formed by currents ..................................... 278
4.5 Creation of the Angolan Unconformities- a summary ...................................... 279
  4.5.1 Interaction of mechanisms- sea-level fluctuations, tectonics, and currents .... 279
  4.5.2 Which mechanisms created the Angolan unconformities ............................. 280
4.6 Conclusion ........................................................................................................... 284

CHAPTER 5 - STRATIGRAPHIC TIMING OF SALT DEFORMATION ............ 285
  5.1 About salt tectonics ......................................................................................... 285
  5.2 Variation along profiles .................................................................................. 289
  5.3 Variation between basins ................................................................................ 292
  5.4 Specific sediment/salt features ....................................................................... 298
    5.4.1 Rafts and pre-rafts .................................................................................... 298
    5.4.2 Evenly-filled (ponded) basins ................................................................. 302
    5.4.3 Asymmetric fill basins .............................................................................. 302
    5.4.4 Pillows ....................................................................................................... 306
    5.4.5 Turtles ....................................................................................................... 311
    5.4.6 Squeezed Basins ...................................................................................... 315
    5.4.7 Massive salt ............................................................................................. 323

CHAPTER 6 - SUMMARY ....................................................................................... 327
  6.1 Introduction ....................................................................................................... 327
  6.2 Evolution of the Angolan margin ..................................................................... 328
  6.3 Sequence stratigraphic framework .................................................................. 330
6.4 Understanding unconformities ................................................................. 331

6.5 Stratigraphic timing of salt deformation .................................................. 333

REFERENCES ................................................................................................. 335

APPENDIX A - REVIEW OF UNCONFORMITIES .......................................... 348

A.1 Introduction .............................................................................................. 348

A.2 History of the term unconformity ............................................................ 349

A.3 Classification systems ............................................................................... 350

A.4 Identifying unconformities on reflection seismic profiles ......................... 353

A.5 Limitations of seismic data ...................................................................... 355
LIST OF ILLUSTRATIONS

Figure 1.1 General map of offshore Angolan basins and seismic lines .................. 2
Figure 2.1 Angolan and Brazilian conjugate margins ........................................ 11
Figure 2.2 Rifting sequences ........................................................................... 13
Figure 2.3 Hotspots ......................................................................................... 14
Figure 2.4 South Atlantic chronozones ............................................................. 15
Figure 2.5 Atlantic hinge zones ...................................................................... 17
Figure 2.6 Rift sequences ................................................................................ 19
Figure 2.7 Large igneous provinces of the Atlantic Ocean ............................... 21
Figure 2.8 Salt basin ....................................................................................... 23
Figure 2.9 Profiles of the Espirito Santo Basin (Brazil) and the Kwanza Basin (Angola)

  with no vertical exaggeration ........................................................................ 25
Figure 2.10 Profiles of the Espirito Santo Basin (Brazil) and the Kwanza Basin (Angola)

  with 3x vertical exaggeration ....................................................................... 26
Figure 2.11 Profile of the Kwanza margin (Angola) .......................................... 30
Figure 2.12 Uplift of Africa relative to the other continents ............................. 32
Figure 2.13 African plateaus .......................................................................... 33
Figure 2.14 Seamounts ................................................................................... 34
Figure 2.15 Stratigraphic column of Angola .................................................. 36
Figure 3.1 Seismic data grid .......................................................................... 40
Figure 3.2 Location of seismic sections on line drawings of Lower Congo Basin seismic

  lines .............................................................................................................. 41
Figure 3.3 Location of seismic sections on line drawings of Kwanza Basin seismic lines ................................................................. 42

Figure 3.4 Location of seismic sections on line drawings of Benguela Basin seismic lines ................................................................. 43

Figure 3.5 Uninterpreted seismic section of the Lower Congo Basin ................................................................. 44

Figure 3.6 Uninterpreted seismic section of the Lower Congo Basin ................................................................. 46

Figure 3.7 Uninterpreted seismic section of the Lower Congo Basin ................................................................. 48

Figure 3.8 Uninterpreted seismic section of the Lower Congo Basin ................................................................. 50

Figure 3.9 Uninterpreted seismic section of the Lower Congo Basin ................................................................. 52

Figure 3.10 Uninterpreted seismic section of the Kwanza Basin ................................................................. 54

Figure 3.11 Uninterpreted seismic section of the Kwanza Basin ................................................................. 56

Figure 3.12 Uninterpreted seismic section of the Kwanza Basin ................................................................. 58

Figure 3.13 Uninterpreted seismic section of the Kwanza Basin ................................................................. 60

Figure 3.14 Uninterpreted seismic section of the Kwanza Basin ................................................................. 62

Figure 3.15 Uninterpreted seismic section of the Benguela Basin ................................................................. 64

Figure 3.16 Uninterpreted seismic section of the Benguela Basin ................................................................. 66

Figure 3.17 Uninterpreted seismic section of the Benguela Basin ................................................................. 68

Figure 3.18 Uninterpreted seismic section of the Benguela Basin ................................................................. 70

Figure 3.19 Uninterpreted seismic section of the Benguela Basin ................................................................. 72

Figure 3.20 Uninterpreted seismic section of the Benguela Basin ................................................................. 74

Figure 3.21 Line drawings of Lower Congo Basin seismic lines ................................................................. 76

Figure 3.22 Line drawings of Kwanza Basin seismic lines ................................................................. 77
Figure 3.23 Line drawings of Benguela Basin seismic lines ................................................. 78
Figure 3.24 Seismic and core acquired by the Deep Sea Drilling Program (DSDP) at site 364 ................................................................................................................................. 80
Figure 3.25 Correlation of DSDP site 364 with seismic line B 2 in the Benguela Basin of this study .......................................................................................................................... 81
Figure 3.26 Sequence boundary chart .................................................................................. 83
Figure 3.27 Major sequence 1 thickness variation .................................................................. 84
Figure 3.28 Seismic section of major sequence 1 in the Kwanza Basin ............................... 86
Figure 3.29 Seismic section of major sequence 1 in the Kwanza Basin ......................... 88
Figure 3.30 Seismic section of major sequence 1 in the Benguela Basin ...................... 90
Figure 3.31 Seismic section of the base of major sequence 1 in the Kwanza Basin ......... 92
Figure 3.32 Seismic section of the base of major sequence 1 in the Benguela Basin ....... 94
Figure 3.33 Seismic section of major sequence 1 in the Lower Congo Basin ................. 97
Figure 3.34 Seismic section of major sequence 1 in the Benguela Basin ..................... 99
Figure 3.35 Seismic section of major sequence 1 in the Benguela Basin ...................... 101
Figure 3.36 Seismic section of major sequence 1 in the Lower Congo Basin ............... 103
Figure 3.37 Seismic section of major sequence 1 in the Kwanza Basin ...................... 105
Figure 3.38 Seismic section of major sequence 1 in the Kwanza Basin ...................... 107
Figure 3.39 Seismic section of major sequence 1 in the Benguela Basin ...................... 109
Figure 3.40 Seismic section of major sequence 1 in the Kwanza Basin ...................... 111
Figure 3.41 Seismic section of erosional truncation under sequence boundary 1 in the Lower Congo Basin ........................................................................................................ 114
Figure 3.42 Seismic section of onlap above sequence boundary 1 in the Kwanza Basin
....................................................................................................................... 116

Figure 3.43 Major sequence 2 thickness variation.......................................................... 118

Figure 3.44 Seismic section of major sequence 2 in the Benguela Basin......................... 120

Figure 3.45 Seismic section of major sequence 2 in the Benguela Basin......................... 122

Figure 3.46 Seismic section of major sequence 2 in the Lower Congo Basin.................. 124

Figure 3.47 Seismic section of sequence boundary 1 in the Kwanza Basin..................... 127

Figure 3.48 Seismic section of sequence boundary 1 in the Lower Congo Basin............. 129

Figure 3.49 Seismic section of major sequence 2 in the Kwanza Basin.......................... 131

Figure 3.50 Seismic section of major sequence 2 in the Kwanza Basin.......................... 133

Figure 3.51 Seismic section of major sequence 2 in the Benguela Basin......................... 135

Figure 3.52 Seismic section of major sequence 2 in the Benguela Basin......................... 137

Figure 3.53 Seismic section of major sequence 2 in the Kwanza Basin.......................... 139

Figure 3.54 Seismic section of major sequence 2 in the Benguela Basin......................... 141

Figure 3.55 Seismic section of major sequence 2 in the Lower Congo Basin.................. 144

Figure 3.56 Seismic section of major sequence 2 in the Benguela Basin......................... 146

Figure 3.57 Seismic section of erosional truncation below sequence boundary 2 in the
Benguela Basin........................................................................................................ 148

Figure 3.58 Seismic section of onlap above sequence boundary 2 in the Kwanza Basin
................................................................................................................................. 150

Figure 3.59 Major sequence 3 thickness variation....................................................... 153

Figure 3.60 Seismic section of major sequence 3 in the Kwanza Basin.......................... 154
Figure 3.61 Seismic section of major sequence 3 in the Kwanza Basin ........................................... 156
Figure 3.62 Seismic section of major sequence 3 in the Kwanza Basin ........................................... 159
Figure 3.63 Seismic section of sequence boundary 2 in the Kwanza Basin .................................... 161
Figure 3.64 Seismic section of major sequence 3 in the Kwanza Basin ........................................... 163
Figure 3.65 Seismic section of major sequence 3 in the Kwanza Basin ........................................... 166
Figure 3.66 Seismic section of major sequence 3 in the Kwanza Basin ........................................... 168
Figure 3.67 Seismic section of major sequence 3 in the Benguela Basin ....................................... 170
Figure 3.68 Seismic section of major sequence 3 in the Benguela Basin ....................................... 172
Figure 3.69 Seismic section of major sequence 3 in the Lower Congo Basin ................................. 174
Figure 3.70 Seismic section of major sequence 3 in the Kwanza Basin ........................................... 176
Figure 3.71 Seismic section of erosional truncation below sequence boundary 3 in the
Benguela Basin ................................................................................................................................. 178
Figure 3.72 Seismic section of onlap above sequence boundary 3 in the Kwanza Basin
...................................................................................................................................................... 180
Figure 3.73 Seismic section of erosional truncation of reflectors of major sequence 3 at
the seafloor in the Kwanza Basin ................................................................................................. 183
Figure 3.74 Seismic section of erosional truncation of reflectors of major sequence 3 at
the seafloor in the Benguela ........................................................................................................ 185
Figure 3.75 Major sequence 4 thickness variation ........................................................................... 187
Figure 3.76 Seismic section of major sequence 4 in the Lower Congo Basin ............................... 189
Figure 3.77 Seismic section of major sequence 4 in the Kwanza Basin .......................................... 191
Figure 3.78 Seismic section of major sequence 4 in the Benguela Basin ........................................ 193
Figure 3.79 Seismic section of major sequence 4 in the Lower Congo basin .................................. 195
Figure 3.80 Seismic section of major sequence 4 in the Lower Congo basin .................................. 197
Figure 3.81 Seismic section of sequence boundary 3 in the Benguela Basin .................................. 200
Figure 3.82 Seismic section of major sequence 4 in the Kwanza Basin ........................................... 202
Figure 3.83 Seismic section of major sequence 4 in the Lower Congo Basin .................................. 204
Figure 3.84 Seismic section of major sequence 4 in the Kwanza Basin ........................................... 206
Figure 3.85 Seismic section of major sequence 4 in the Benguela Basin ........................................... 208
Figure 3.86 Seismic section of major sequence 4 in the Lower Congo Basin .................................. 210
Figure 3.87 Seismic section of major sequence 4 in the Benguela Basin ........................................... 212
Figure 3.88 Seismic section of major sequence 4 in the Kwanza Basin ........................................... 214
Figure 3.89 Seismic section of major sequence 4 in the Lower Congo Basin .................................. 216
Figure 3.90 Seismic section of erosional truncation of reflectors of major sequence 4 at the seafloor in the Benguela Basin ......................................................................................... 219
Figure 3.91 Seismic section of erosional truncation of reflectors of major sequence 4 at the seafloor in the Kwanza Basin ......................................................................................... 221
Figure 3.92 Detailed sequence stratigraphic interpretation of the Lower Congo Basin with seismic section, interpretation, and chronostratigraphic chart .................................................. 225
Figure 3.93 Detailed sequence stratigraphic interpretation of the Kwanza Basin with seismic section, interpretation, and chronostratigraphic chart .................................................. 234
Figure 3.94 Detailed sequence stratigraphic interpretation of the Benguela Basin with seismic section, interpretation, and chronostratigraphic chart .................................................. 241
Figure 4.1 Seismic data grid ................................................................................................................. 248
Figure 4.2 Location of seismic sections on line drawings of the Angolan seismic lines 249

Figure 4.3 Mesozoic and Cenozoic eustatic curve ......................................................... 254

Figure 4.4 Uninterpreted and interpreted seismic section displaying a unconformity

related to sea-level change in the Lower Congo Basin ............................................. 256

Figure 4.5 Uninterpreted and interpreted seismic section displaying a unconformity

associated with tectonics in the Kwanza Basin ....................................................... 261

Figure 4.6 Uninterpreted and interpreted seismic section displaying a unconformity

related to salt tectonics in the Benguela Basin ....................................................... 264

Figure 4.7 Oceanic currents change through time in the Atlantic Ocean .................. 268

Figure 4.8 Surface currents of the South Atlantic Ocean ........................................... 270

Figure 4.9 Change in world oceanic circulation due to plate tectonics ...................... 272

Figure 4.10 Current erosion by the Brazilian current ................................................. 275

Figure 4.11 Bottom current erosion in the North Scotia Ridge region ...................... 276

Figure 4.12 Seismic section of current erosion at the seafloor in the Kwanza Basin ..... 277

Figure 5.1 Salt models of active piercement and downbuilding ................................ 288

Figure 5.2 Profile of the Kwanza Basin ..................................................................... 290

Figure 5.3 Salt tectonic map offshore Angola ............................................................ 293

Figure 5.4 Depth converted profiles of the Lower Congo, Kwanza, and Lower Congo

Basins ....................................................................................................................... 294

Figure 5.5 Conceptual diagram of the salt basin during salt deposition .................. 295

Figure 5.6 Free-air gravity map offshore Angola ....................................................... 297

Figure 5.7 Diagram of raft evolution ........................................................................ 299
Figure 5.8 Map of distribution of rafts offshore Angola and location of seismic example ................................................................. 300

Figure 5.9 Seismic section of rafts in the Kwanza Basin .................................................. 301

Figure 5.10 Diagram of evenly-filled minibasin evolution ........................................... 303

Figure 5.11 Map of distribution of evenly-filled minibasins offshore Angola and location of seismic example ................................................................. 304

Figure 5.12 Seismic section of evenly-filled minibasins in the Kwanza Basin ............. 305

Figure 5.13 Diagram of asymmetric fill minibasin evolution ..................................... 307

Figure 5.14 Map of distribution of asymmetric fill minibasins offshore Angola and location of seismic examples ................................................................. 308

Figure 5.15 Seismic section of an asymmetric fill minibasin in the Benguela Basin .... 309

Figure 5.16 Seismic section of an asymmetric fill minibasin in the Kwanza Basin ....... 310

Figure 5.17 Diagram of pillow evolution ..................................................................... 312

Figure 5.18 Map of distribution of pillow offshore Angola and location of seismic example ................................................................................................. 313

Figure 5.19 Seismic section of a pillow in the Kwanza Basin ...................................... 314

Figure 5.20 Diagram of turtle evolution ...................................................................... 316

Figure 5.21 Map of distribution of turtles offshore Angola and location of seismic examples ................................................................................................. 317

Figure 5.22 Seismic section of a turtle in the Lower Congo Basin .......................... 318

Figure 5.23 Seismic section of a turtle in the Kwanza Basin ...................................... 319

Figure 5.24 Diagram of squeezed minibasin evolution ........................................... 320
Figure 5.25 Map of distribution of squeezed minibasins offshore Angola and location of seismic example................................................................. 321

Figure 5.26 Seismic section of squeezed minibasins in the Lower Congo Basin........322

Figure 5.27 Map of distribution of massive salt offshore Angola and the location of seismic examples................................................................. 324

Figure 5.28 Seismic section of massive salt in the Benguela Basin ...................... 325

Figure 5.29 Seismic section of the massive salt with possible internal thrusts in the Kwanza Basin ................................................................. 326

Figure A.1 Types of unconformities ............................................................... 351

Figure A.2 Reflector termination patterns....................................................... 354

Figure A.3 Seismic model of an outcrop......................................................... 356

Figure A.4 Seismic model of an outcrop......................................................... 357

Figure A.5 Seismic model of an outcrop......................................................... 358
CHAPTER 1 - INTRODUCTION

1.1 Objectives

Sequences are recognized throughout the geologic record. The Angolan margin and its available seismic data grid provides an excellent opportunity to examine the factors that control the deposition and preservation of sediments in sequences, as well as the factors that create the erosion or non-deposition along sequence boundaries. The Angolan sequences can be compared to global sequence charts and used to investigate the effects of local events versus global events on the area's sequences.

This study strives to accomplish several objectives. The tectonic evolution of the Angolan margin is reviewed. The sequence stratigraphic framework of Angola is established. The sequences are compared with the global sequence charts as well as with events that are global, regional, and local. These events include sea-level changes, tectonic events, and changes in oceanic circulation. The formation of the sequence bounding unconformities is examined. Within the sequences, the interaction of sedimentation and salt movement is described.

1.2 Study Area

The Angolan segment of the West African passive margin contains three offshore basins. From north to south, these three basins are the Lower Congo, Kwanza, and Benguela Basins (Figure 1.1). This study examined the sequence stratigraphic evolution of these
Figure 1.1 - Location map of the offshore Angolan basins, the Lower Congo, Kwanza, and Benguela Basins. The location of the basin boundaries, the Congo River (solid line), Ambriz Arch (dashed line), and the seamounts (open circles), are noted. The Walvis Ridge, the southern boundary of the Benguela Basin, is located at approximately 19°S. Traces of the sixteen reflection seismic lines interpreted in this study are thick black lines. The position of the DSDP site 364 is the black dot.
basins. The study area is located between 6°S and 13°S, and 10°E and 14°E. The area covered by the study is approximately 300 by 850 kilometers (255,000 km²).

The extent of the offshore Angolan basins is defined by physical structures (Figure 1.1). The Angolan part of the Lower Congo Basin is bounded on the north by the canyon of the Congo River at approximately 6°S. The boundary between the Lower Congo Basin and the Kwanza Basin is the Ambriz Arch located between 7°S and 8°S (Standlee et al., 1992). The boundary between the Kwanza and Benguela Basins is the chain of seamounts at approximately 11°S (Spencer et al., 1998 and Brock et al., 1998). The southern boundary of the Benguela Basin, which separates the basin from the Namibe Basin, is the Walvis Ridge (Lehner and de Ruiter, 1977).

The study area extended from the shelf region to the abyssal plain in each of the three basins. While the Kwanza Basin does extend onshore (Brognon and Verrier, 1966), only the offshore portion is included in this study. The range of water depths covered in the basins is from 100 meters or less to four kilometers.

1.3 Data Set

The data set of this study included a 2D reflection seismic grid and well data from a Deep Sea Drilling Program (DSDP) Site (Bolli and Ryan, 1978) (Figure 1.1).
The reflection seismic grid is a combination of various vintages of seismic data acquired by Western Geco. The acquisition dates of the seismic data range between the early 1970s and 1998. The older data covers the shelf region. The recent acquisition of high-quality regional reflection seismic lines extended from the earlier shelf lines to the ultra-deep water area (water depth > 1000 meters). The recent acquisition also covered the shelf region of the Benguela Basin.

The processing of the seismic data, including migration, was not part of this study. As with the data acquisition, the seismic data processing was performed in various years. The different vintages of data were processed with different processing flows and algorithms.

The 2D regional seismic grid interpreted for this study consists of twelve dip lines and four strike lines (Figure 1.1). The seismic line lengths add up to 5750 kilometers of data. The spacing between lines varies between 20 and 100 kilometers. The three seismic dip lines in the Lower Congo Basin are separated by about 50 kilometers. There are three strike lines through the Lower Congo Basin, the fourth strike line does not extend northward through the basin. The Lower Congo strike lines are separated by 50 to 75 kilometers. The distance between the Lower Congo and Kwanza dip lines is less than 50 kilometers. The Kwanza Basin dip lines are spaced at 50 to 75 kilometers, while the strike lines are spaced at 50 to 100 kilometers. The Kwanza and Benguela Basins profiles are separated by approximately 100 kilometers. The Benguela Basin dip lines
are spaced at 20 to 75 kilometers, while the strike lines are spaced at 50 to 100 kilometers.

Well data from DSDP site 364 was primarily used to constrain ages of the horizons interpreted on the seismic lines. In 1975, 296 meters of core was recovered from a 428 meter section at site 364 (Bolli and Ryan, 1978). The position of the well is 11°34.32'S, 11°58.30'E (Figure 1.1) (Bolli and Ryan, 1978). The water depth at this position is approximately 2450 meters (Bolli and Ryan, 1978). A number of measurements were taken and analyses were performed on the core by the shipboard scientific party. These measurements include sonic velocity, bulk density, shear strength, porosity, lithology, biostratigraphy, and paleontology (Bolli and Ryan, 1978). The measured velocity of the cored units allowed the correlation of the core to a reflection seismic section across site 364. Comparison of this study's seismic profiles and the DSDP seismic and well data allowed correlation of cored, dated units to seismic units and horizons. The lithologic data of the core provide a framework for the interpretation of the deep water portions of the seismic sequences. The planktonic foraminifers, benthic foraminifers, calcareous nannoplankton, and radiolarians were studied by the shipboard scientific party (Bolli and Ryan, 1978). The biostratigraphy and paleontology of the core provided ages for the unconformities and horizons in the core and on the seismic sections (Bolli and Ryan, 1978).
1.4 Methodology

The study is based on the analysis of seismic sequence stratigraphy. The interpretation of the seismic data follows the principles described in the AAPG Memoir 26 – Seismic Stratigraphy-applications to hydrocarbon exploration (Mitchum et al., 1997; Sheriff, 1977; and Vail et al., 1977), AAPG Studies in Geology 15 – Seismic Expression of Structural Styles (Bally, 1983), and AAPG Studies in Geology 27 – Atlas of Seismic Stratigraphy (1987) (Bally, 1987, Shell Oil Company, 1987, and Vail, 1987). The analysis of the seismic data includes both an evaluation of individual reflectors and patterns of a group of reflectors. Individual reflectors can vary in geometry, amplitude, frequency, continuity, and termination style. Patterns of a group of reflectors can may be parallel, subparallel, divergent, prograding clinoforms, or chaotic (Vail et al., 1977). Using the termination patterns of reflectors, unconformities can be interpreted. Using sequence stratigraphic principles, the record is separated into depositional sequences bounded by unconformities and their correlative conformities (Mitchum et al., 1977).

The sequences and their unconformities are correlated within each basin as well as between basins where possible with confidence. Major sequences were identified that could be interpreted throughout and between the three basins with a high degree of confidence. Additional sequences within these major sequences were interpreted within a basin, but could not be correlated to the adjacent basin with a high degree of confidence. Detailed interpretation of the sequence stratigraphic significance of each reflector was
performed on three profiles, one for each basin. Chronostratigraphic charts were constructed using the detailed interpretation of the profiles.

Within the interpreted sequence stratigraphic framework, the timing and mechanics of the formation of salt structures was examined. The Angolan basins contain a variety of salt tectonic features. The reflectors of strata adjacent to the salt features were used to determine the timing and mechanics of the salt structure formation.
CHAPTER 2 - TECTONIC EVOLUTION OF THE ANGOLAN MARGIN

2.1 General evolution

The geological development of the offshore Angolan basins is traced back to the supercontinent of Pangea. The metamorphic basement of the Angolan basins formed by the Pan African/Brasiliano orogeny during the beginning of the Phanerozoic (Burke et al., 1977; Kroner, 1980; and Gerrard and Smith, 1982). Initiated during the Jurassic, the breakup of Pangea and the formation of the Atlantic Ocean began with regional uplift and volcanism with the rupture of the continental crust (Emery and Uchupi, 1984 and Standlee et al., 1992). The African and South American continents separated. The separation began at the southern end of Pangea and migrated to the north (Nurnberg and Muller, 1991). Lacustrine deposits were formed during the rifting stage in the Jurassic and Early Cretaceous (Brice et al., 1982; McHargue, 1990; Henry et al., 1995; and Braccini et al., 1997). Oceanic crust was implaced along the mid-oceanic ridge. To the south of the Angolan basins, oceanward divergent reflectors (ODRs) represent the accretion of oceanic crust during initial seafloor spreading (Abreu, 1998 and Talwani and Abreu, 2000). These ODRs are either not present or not seismically observable under the Angolan basins. As marine waters formed the early ocean, physical barriers restricted the flow of the saline waters. In the Aptian, salt layers formed, filling the early post-rift basins (Belmonte et al., 1965; Pautot et al., 1973; Burke, 1975; Evans, 1978; de Ruiter, 1979; and Hardie, 1990). Once the marine incursion was established, a margin section developed along the basins as a result of drifting, thermal cooling, and subsidence
(Emery et al., 1975; Lehner and de Ruiter, 1977; Rabinowitz and LaBrecque, 1979; Keen and Beaumont, 1990; Poag and de Graciansky, 1992; Uchupi, 1992; Walgenwitz et al., 1992; and Marton et al., 2000). Shallow water carbonates developed during the Albian time (Brognon and Verrier, 1966; Tillement, 1987; Walgenwitz et al., 1990; and Ala and Selley, 1997). Clastic deposition followed along with westward tilting of the margin (Gerrard and Smith, 1982; Walgenwitz, et al., 1992; Platt et al., 1993; Ala and Selley, 1997; and Marton et al., 2000). The combination of the sedimentation and the tilting, stimulated the movement of the salt layers (Duval et al., 1992; Lundin, 1992; and Maudit et al., 1997). Subsequent deposition was influenced by and in turn influences the development of salt structures (Baumgartner and van Andel, 1971; Kneller and McCaffrey, 1995; and Spathopoulos, 1996). An interplay of salt movement and sediment deposition dominated the Tertiary development of the basins. The uplift and erosion of Africa also sourced and affected the Tertiary sedimentation (Bond. 1978; Sahagian, 1988; Lunde et al., 1992; and Nyblade and Robinson, 1994). The three basins offshore Angola are separated by physical barriers and by their sedimentary histories.

2.2 Pre-rifting

The basement of the Angolan basins consists of faulted metamorphic rocks (Gerrard and Smith, 1982). Overlying this basement are prerift clastics. These clastics have been penetrated by wells onshore as well as offshore on the Angolan shelf and consist of massive, clean, well-sorted sands and siltstones (Brice et al., 1982 and Gerrard and Smith, 1982). These clastics were presumably deposited in a broad, shallow lake system
in a gently subsiding intracratonic basin. This prerift sequence is over 1 kilometer thick in some wells (Brice et al., 1982 and Gerrard and Smith, 1982). Rifting has faulted and rotated the layers. The age of the prerift clastics range from Jurassic until the initial rifting in the Cretaceous (Brice et al., 1982 and Gerrard and Smith, 1982). The prerift sequence is topped by volcanics that herald the beginning of the rifting phase. (Brice et al., 1982)

2.3 Rifting

The breakup of Pangea initiated during the Early Jurassic between North America and Africa (Emery and Uchupi, 1984). South America and Africa separated along the South Atlantic Rift beginning in the south during the Jurassic and progressing northward (Nurnberg and Muller, 1991). The rifting of the Angolan and Brazilian margins began in Early Cretaceous, Berriasian time and continued along the Angolan coast and its conjugate Brazilian coast through the Neocomian to the Aptian (Karner et al., 1997 and Karner and Driscoll, 1999). The rifting may have initiated by hotspots and propagated from these points (Standlee et al., 1992). The Brazilian basins that are conjugate to the Lower Congo, Kwanza, and Benguela Basins are the Espirito Santo and Campos Basins (Figure 2.1) (Cainelli and Mohriak, 1998). The Angolan and Brazilian basins share the same pre-rift and initial rifting history. Both the Angolan and Brazilian side of the rift have hinge zones that may correlate (Karner and Driscoll, 1999). The Angolan syn-rift deposits indicate three phases of rifting. Each phase produced an unconformity bound sequence (Karner et al., 1997). A cartoon of the Angolan side of the
Figure 2.1: Early Cretaceous position of Brazilian and Angolan sedimentary basins (modified from Cainelli and Mohriak, 1998).
rift displays the rifted Pre-Cambrian basement and the three syn-rift sequences (Figure 2.2).

According to Standlee et al. (1992), the South Atlantic Rift system may have been initiated by two hotspots, the Walvis hotspot and the Benue triple junction. The Walvis hotspot is located to the south of the Benguela Basin, the southernmost Angolan basin. The Benue triple junction is located off the coast of Gabon to the north of the Angolan margin. The initial breaks occurred over the two hotspots. Megafractures propagated away from the hotspots and linked in the vicinity of NW Gabon/NE Brazil, north of Angola (Figure 2.3) (Standlee et al., 1992).

The continents of Africa and South America separated during the Early Cretaceous. The age of the South Atlantic oceanic crust is used to reconstruct the plate positions and movements. The oldest oceanic crust recognized off the coast of Angola is associated with chronozone M3, about 124 to 127 Ma (Figure 2.4) (Cande et al., 1989). The timing and location of the oceanic/continental transition is limited by the Cretaceous magnetic quiet zone.

During the rifting phases, two major tectonic hinge zones developed along the West African margin (Karner and Driscoll, 1999). The Eastern Hinge Zone is located onshore Angola. The Atlantic Hinge Zone is located offshore of Angola, but to the north of Angola, it is also onshore. Both of the hinge zones trend subparallel to the margin
Figure 2.2: Cartoon of the evolution of the Angolan margin.
Figure 2.3: Location of the Walvis hotspot and Benue Triple junction. Rifting along this segment of the African margin may have initiated at these hotspots and propagated along the dashed lines. Arrows along the dashed lines indicate the direction of propagation. The Benguela, Kwanza, and Lower Congo basins would have rifted by the northward propagation from the Walvis hotspot (Standlee et al, 1992).
Figure 2.4: South Atlantic chronozones- The M3 chronozone offshore Angola is highlighted by the arrow. The M3 chronozone formed about 124 to 127 Mya. There is a magnetic quiet zone that limits the timing and location of the oceanic/continental transition offshore West Africa. The oceanic/continental transition is between the C34n (99? to 120 Mya) and M3 (124 to 127 Mya) chronozones (modified from Cande et al, 1989).
(Figure 2.5). The Eastern Hinge Zone separates syn-rift deposits to the west from Precambrian basement to the east. Therefore, the Eastern Hinge Zone is the eastern limit of extension. The Atlantic Hinge Zone is located on offshore profiles under the current shelf/slope transition. The Atlantic Hinge Zone is interpreted as a series of en echelon, high-standing blocks, rather than continuous (Karner and Driscoll, 1999).

The two West African hinge zones may be related to two hinge zones located on the eastern Brazilian margin (Karner and Driscoll, 1999). Both the western/onshore and the Alagoas Hinge trend subparallel to the Brazilian margin. The western/onshore hinge zone separates the syn-rift deposits to the east from the Precambrian basement to the west. The Alagoas Hinge is a relatively continuous series of highstanding basement blocks. As the Atlantic Hinge Zone, the Alagoas Hinge separates shallow and onshore depocenters from deeper water depocenters (Figure 2.5) (Karner and Driscoll, 1999).

The hinge zones were formed by rift-induced uplift (Karner and Driscoll, 1999). The area on the landward side of a hinge zone experiences crustal unloading. This force creates the faults along the hinge zone. The Eastern Hinge Zone formed when rifting began in the South Atlantic. The hinge zone was the eastern limit of significant extension and depocenters during rifting (Karner and Driscoll, 1999).

The Atlantic Hinge Zone developed during a later rifting phase (Karner and Driscoll, 1999). During the second major phase of extension, the main axis of rifting shifted to the
Figure 2.5: Location maps showing the major tectonic and structural features along the eastern Brazilian and western African continental margins. The base maps are offshore crustal Bouguer gravity anomaly of the regions. The onshore western Hinge Zone (Brazil) and the Eastern Hinge Zone (Africa) are identified by a thin red line and demarcate, respectively, the western and eastern limit of Neocomian extension and separates continental margin sediments from Precambrian basement. The Alagoas hinge zone (Brazil) and Atlantic Hinge Zone (Africa) are identified by a thick red line. The ocean-continental boundary, approximately delineated by the strong positive-negative gradient in the gravity anomaly, is shown as a bold blue line (Karner and Driscoll, 1999).
west. The westward shift of the rifting created the Atlantic Hinge Zone and its basinward depocenters. The Atlantic Hinge Zone marks the eastern limit of the later phases of rifting (Karner and Driscoll, 1999).

The sediments deposited during the rifting process indicate that the rifting occurred in multiple events (Figure 2.6) (Karner and Driscoll, 1999). In a study located just to the north of Angola, off the coast of Cabinda and Gabon, Karner et al. (1997) interpret three phases of rifting with unconformity bounded synrift sediment packages. The first phase of rifting occurred during early Berriasian time. The extension formed a series of deep, anoxic lacustrine systems with an eastern extent marked by the Eastern hinge zone. The Berriasian to Hauterivian synrift package consists of shoaling upward lacustrine deposits. During the second rift phase, the extension shifted westward of the Eastern hinge zone to the Atlantic hinge zone. Between Hauterivian and late Barremian time, the second synrift package consists of deep water lacustrine facies grading upward into shallow lacustrine shale and sand and alluvial deposits. The third and final rifting event beginning in the late Barremian breaches the continent, allowing the first emplacement of oceanic crust. The base of the final rifting is the breakup unconformity. The deposits of the third synrift package begins with deep water lacustrine sediments and ends with marine sediments. Karner et al. (1997) interpret the South Atlantic rifting to have developed in three phases from an initially broadly distributed continental rifting to more focused rifting as the extension migrated to the west. The three rifting phases are recognized in the synrift sediment packages (Kamer et al., 1997).
Figure 2.6: Syn-rift deposits off the coast of Congo and Cabinda are separated into 3 phase of rifting each bounded by unconformities (modified from Kerner et al, 1997).
2.4 Oceanward divergent reflectors

Seaward dipping reflectors (SDRs) or oceanward divergent reflectors (ODRs) are interpreted on seismic lines to the south of the Angolan basins, offshore Namibia (Abreu, 1998). Boreholes have confirmed that the SDRs are thick basaltic flows (Abreu, 1998). The interfingered or overlying sediments tend to be subaerial or freshwater deposits (Abreu, 1998). The SDRs represent the main volcanic activity prior to ocean crust formation (Talwani and Abreu, 2000). In offshore Angola, SDRs are not visible. Although the pre-salt reflectors are heavily distorted by the fast velocities and varying shape of the salt structures, some areas provide relatively clear views of pre-salt reflectors. In the Angolan basins the pre-salt reflectors do not resemble SDRs. The pre-rift setting of the Angolan basins was quite different from the setting to the south in Namibia (Gerrard and Smith, 1982; Brice et al., 1982; and Abreu, 1998). Figure 2.7 is a map of the large igneous provinces of the South Atlantic (Mahoney and Coffin, 1997). The southern margins of Africa and South America are volcanic passive margins with ODRs. The basins of Benguela and Campos and northward do not contain ODRs (Cainelle and Mohriak, 1998).

2.5 Post rift sedimentation

Above the syn-rift sequences is a sandstone. In the Lower Congo Basin, the sandstone is the Chela Formation (Ala and Selley, 1997 and Marton et al., 2000). In the Kwanza and Benguela Basins, the sandstone is the Cuvo Formation (Ala and Selley, 1997 and Marton et al., 2000). These initial postrift deposits vary in thickness. The thickest deposits occur
Figure 2.7: Large igneous provinces of the Atlantic Ocean are identified in red. The image contains combined global seafloor topography and land topography derived from the USGS 30 arc-second digital elevation model (Mahoney and Coffin, 1997).
in the Kwanza Basin and are 200 meters thick. The Cuvo/Chela Formations represent the beginning of marine deposition along the Angolan margin (Ala and Selley, 1997 and Marton et al., 2000).

2.6 Salt
The synrift and initial postrift deposits are topped by the Aptian salt, the Loeme evaporites off the Angolan margin (Figure 2.2) (Belmonte et al., 1965; Pautot et al., 1973; Burke, 1975; Evans, 1978; and de Ruiter, 1979). The salt was deposited in a basin extending from the Walvis ridge to south of Nigeria and the Sergipe/Alagoas Basin (Figure 2.8) (Burke, 1975 and Evans, 1978). The initial thickness of the salt sequence varied with thicker deposits of over one kilometer along the southern Angolan margin and thinner deposits to the north. The salt sequence is predominantly halite, but also includes carnallite, bischofite, tachyhydrite, anhydrite, and dolomite (de Ruiter, 1979). The chemical composition of the salt varies along the margin. In the northern portion of the Angolan basins, the salt composition suggests that the salt water was enriched in highly soluble components, while the salt of the southern portion of the Angolan basins has a balanced composition of halite, anhydrite, and dolomite (de Ruiter, 1979 and Karner et al., 1997). The outer deposits may be evaporite or shale equivalents to the Loeme deposits (Karner and Driscoll, 1999).

Two theories for the formation of the salt are evaporative processes or hydrothermal brines. Scruton (1953) describes how salts are formed by evaporation through more
Figure 2.8: The Aptian salt basin extended from the Walvis ridge to south of Nigeria and Sergipe/Alagoas basin (modified from Cainelli and Mohriak, 1998).
evaporation than precipitation and runoff. Burke (1975) describes a method of evaporite formation through the isolation of rifted areas by topographical barriers (sills). Periodic influx of saline waters into the rifted areas and isolation by the sills allow for the deposition of thick salt layers along the Angolan margin. Hardie (1990) suggests that evaporites are formed by hydrothermal brines during rifting. Evidence for Hardie’s theory is the MgSO4-poor salts in the ancient rift areas.

2.7 Post salt units

Overlying the salt layer is a thick package of carbonate and clastic sediment (Figure 2.2) (Brognon and Verrier, 1966; Gerrard and Smith, 1982; Platt et al., 1993; Ala and Selley, 1997; and Marton et al., 2000). The post salt history of the African and Brazilian margins are similar. The Figures 2.9 and 2.10 compare the conjugate basins of Espirito Santo and Kwanza without vertical exaggeration and with three times vertical exaggeration (Cainelli and Mohriak, 1998 and Marton et al., 2000). The Brazilian and Angolan margins are similar in several aspects. The age and distribution of sediments are very similar. Both margins have extensive salt tectonics. Salt diapirs and a massive salt at the seaward edge of the basins developed along both margins. The thicknesses of the sedimentary packages are comparable. Additionally, the width of the margin, between 200 and 250 km, is the same for the Espirito Santo and Kwanza Basins.

The post salt units vary between the three basins offshore Angola. The first deposits of Albian carbonate, Pinda and equivalents, were thicker in the shallow marine regions and
Figure 2.9: Profiles of the Brazilian and Angolan margins with no vertical exaggeration. The Brazilian profile is located in the Espirito Santo Basin (Cainelli and Mohriak, 1998). The Angolan profile is located in the Kwanza Basin (Marton et al, 2000). The profiles are drawn at the same scale. The colored units represent the same age deposits.
Figure 2.10: Profiles of the Brazilian (a) and Angolan (b) margins with 3x vertical exaggeration. These profiles are displayed at a 1:1 vertical to horizontal scale in figure 2.9 with a color legend. a) The Brazilian profile is located in the Espírito Santo Basin (Cainelli and Mohriak, 1998). The Brazilian and Angolan profiles are drawn at the same scale. The colored units represent the same age deposits.
Figure 2.10: Profiles of the Brazilian (a) and Angolan (b) margins with 3x vertical exaggeration. These profiles are displayed at a 1:1 vertical to horizontal scale in figure 2.9 with a color legend. 

b) The Angolan profile is located in the Kwanza Basin (Marton et al, 2000). The profiles are drawn at the same scale. The colored units represent the same age deposits.
in the south of Angola. The deposit of the carbonate was only slightly affected by the salt layer. The burden of the carbonate on the salt initiated movement of the salt and subsequent deformation of the overlying deposits. Beginning in the Albian, overburden of only a few hundred meters began to extend, forming small, tilted rafts (Duval et al., 1992; Lundin, 1992; and Maudit et al., 1997).

Late Cretaceous clastic sediment entered the basin via erosion of continental deposits and fluvial transport. The clastic deposits were thicker in the Lower Congo and Benguela Basins, while thin in the Kwanza Basin. The difference in the thickness of Late Cretaceous clastics may have been due to varied drainage basins onshore. During the Late Cretaceous, sedimentation was directed into depocenters created by previous salt/sediment movement. The burden created by the sedimentation added to the overburden, encouraging more salt/sediment movement. The interplay of salt and sedimentation created the salt structures and the sediment depocenters throughout the basins (Baumgartner and van Andel, 1971; Kneller and McCaffrey, 1995; and Spathopoulos, 1996).

During the Tertiary, clastic deposition continued. The largest sedimentary input was into the Lower Congo Basin, with the Benguela Basin a close second, and the Kwanza Basin lagging behind. The deposits were disrupted by strong westward tilting of the basin (Duval et al., 1992; Lundin, 1992; and Maudit et al., 1997). The tilting in combination with the rapid rate of sedimentation furthered the development of salt structures. In the
lower slope region, the basins developed salt walls, diapirs, canopies, and other structures (Baumgartner and van Andel, 1971; Kneller and McCaffrey, 1995; and Spathopoulos, 1996). The profile of the margin became segregated into distinct provinces (Figure 2.11) (Marton et al., 2000). The easternmost province is extensional, containing growth faults, rafts, and pre-rafts. The central province consists of salt withdrawal minibasins. In the center of the Angolan basins, salt diapirs and walls separate sediment depocenters. The westernmost province has contractional folds and thrusts. The contraction in the western portion of the basins balanced the extension updip. The sediments overlying the massive salt in the west were folded. Thrust faults occurred within the salt and at the westernmost extent of the salt body. The total extension in the extensional region of the margin was balanced by the contraction in the thrust and fold region of the margin. Marton et al. (2000) measured 13 km of extension in the raft (extensional) domain, 3 km of shortening in the diapir (salt withdrawal) domain, and 10 km of shortening in the canopy/massive salt (fold and thrust) domain. From the Early Cretaceous to the present, the interplay of sedimentation and salt defined the Angolan offshore basins.

2.8 Tertiary uplift

The African continent has been uplifted relative to the other continents (Bond, 1978; Sahagian, 1988; Lunde et al., 1992; and Nyblade and Robinson, 1994). Since the Miocene, and possibly beginning in the Eocene, Africa been elevated relative to North America, South America, Europe, and Australia. Bond (1978) used the percentage of
Figure 2.11: Profile of the Angolan margin, Kwanza Basin, with no vertical exaggeration. The Angolan margin can be separated into three regions along a dip profile. The easternmost region contains growth faults, normal faults, and rafts. This area is called the Extensional platform. The middle portion of the offshore Angolan basins in the Salt withdrawal minibasin region. A variety of salt structures have formed in this area, including diapirs, walls, canopies, pillows, and domes. The westernmost portion of the basins is the Contractional fold and thrust region. Contractional features such as folds and thrust faults in the sediments and within the massive salt occur in this area.
flooding on hypsometric curves to illustrate that Africa was higher than other continents since at least the Miocene (Figure 2.12). Additional evidence of uplift is supplied by combinations of seismic and outcrop studies, maturity profiles from wells, sediment distribution (Lunde et al., 1992), and regional studies of shoreline deposits (Sahagian, 1988 and Bond, 1978). Onshore uplift has continued since the Miocene. Up to 1-2 km of sediments have been eroded onshore and redeposited westward. Significant portions of the eroded sediments accumulate in elongated Tertiary troughs. These troughs contain up to 3 km of Miocene sediments (Lunde et al., 1992). The surface of the African continent has been elevated by between a few hundreds of meters to more than one kilometer. Plateaus are located in Eastern Africa, South Africa, and the Southeastern Atlantic Ocean (Figure 2.13). The combination of these plateaus is referred to as the African superswell (Nyblade and Robinson, 1994). The superswell may be due to heating of the lithosphere. Since the Miocene, the onshore areas of Africa have been uplifted. The only areas that subsided were offshore areas. These offshore areas subsided due to the westward tilting of the margin by thermal cooling. The hinge line between the uplifting onshore and the westwardly tilting offshore areas is roughly the present coastline (Lunde et al., 1992).

2.9 Seamounts

Separating the Kwanza and Benguela Basins is a chain of volcanic seamounts. The chain trends west-northwest to east-southeast (Figure 2.14). Hotspot tracks in the eastern portion of the South Atlantic, as well as on the African continent, trend northeast-
Figure 2.12: a) Continental hypsometric curves. The African curve indicates that Africa was uplifted relative to the other continents. The continental hypsometric curves are drawn so that the area between -200 m and the highest land elevations has been normalized to 100%. Triangles are the percentages of areas flooded during the Eocene; open circles are percentages of the areas flooded during the Miocene. The dashed segments for Africa is Africa’s hypsometric curve restored to its approximate Late Cretaceous shape.
b) During both the Eocene and Miocene, Africa has higher elevations relative to the other continents. Each bar is the range of elevation between the two percentages of flooding calculated for each age on each continent; i.e., between the percentage computed assuming complete submergence of shelves and the percentage assuming complete emergence of the shelves. The dashed bar for Africa is the range of values plotted on the restored Late Cretaceous curve (Bond, 1978).
Figure 2.13: Map of the uplift within the African continent during the Tertiary. The map is the Cenomanian surface corrected for sediment loading by post-Cenomanian sediments. Sahagian 1988 suggests Late Cretaceous or Tertiary uplift by the relatively slow absolute motion of Africa. Bond 1978 suggests Late Tertiary uplift, probably post-Miocene. The maximum amount of uplift is 2-3 km (Lunde, 1991).
Figure 2.14: Location of seamounts is highlight by arrows. The map on the left is the bathymetry/topography of the Angolan segment of the South Atlantic region based on satellite and ship data, adapted from Smith and Sandwell, 1997. Version 8.2 was used to generate the bathymetry/topography map. The bathymetry contour lines represent 1000 meters. The unit of the color scale is meters. The map on the right is the free-air gravity map of the Angolan segment of the South Atlantic based on satellite data, adapted from Sandwell and Smith, 1997. Version 9.2 was used to generate the free-air gravity map. The unit of the color scale is mGal.
southwest. The direction of the hotspot trends correlates with the movement of Africa and the oceanic crust away from the mid-oceanic spreading ridge. The chain of seamounts between the Kwanza and Benguela Basins does not match these hotspot chains. The mechanism forming the chain appears to be different from the hotspot mechanism.

2.10 Stratigraphic columns

The Angolan basins have similar stratigraphic columns of metamorphic basements, pre-rift sediments, volcanics, syn-rift deposits, salt layers, carbonates, and clastics (Figure 2.15). The basement of each of the three offshore Angola basins is a Pre-Cambrian faulted gneiss. The first sediments above the metamorphic basement are Jurassic coarse continental clastics. Interbedded volcanics erupted at the Jurassic-Cretaceous boundary. In the Lower Congo Basin, these pre-rift volcanic deposits are the Zenze and Lucula Formations. While in the Kwanza and Benguela Basins, the equivalent deposits are the base of the Maculungo Formation. The initiation of rifting is associated with volcanics during the Neocomian. The volcanic conglomerates and tuffs are part of the Lucula and Maculungo Formations. Above the volcanics are organic rich shales. In the Lower Congo Basin the organic zone is part of the Bucomazi Formation. The Bucomazi Formation consists of the organic zone and an overlying/interfingering lacustrine limestone Toca Formation. In the Kwanza and Benguela Basins, the top of the Maculungo Formation consists of shales, halite, and limestone. The carbonates were
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Figure 2.15: Stratigraphic column for the offshore Angolan Basins. The formation names and descriptions are listed for the Lower Congo Basin and for the Kwanza and Benguela Basins. Based on Brognon and Verrier 1966, Schlumberger 1983, and Marton at el, 2000.
deposited as lacustrine shoals near the end of the Neocomian and beginning of the Barremian. The marine incursion creates a late Barremian to early Aptian peneplanation. A transgressive sandstone overlays this unconformity. The Aptian sandstone is the Chela Formation in the Lower Congo and the Cavo Formation in the Kwanza and Benguela Basins (Broignon and Verrier, 1966; Schlumberger, 1991; Ala and Selley, 1997; and Marton et al., 2000).

The next layer deposited is referred to as the Aptian salt. The Aptian salt contains anhydrite, halite, and other evaporites. The formation name for the Aptian salt is Loeme. Above the massive salt layer, the evaporite is interbedded with dolomite and limestone in the Albian and Cenomanian. In the Lower Congo Basin, these layers are the Mavuma, Vermelha, Pinda, and Moita Seca Formations. The Moita is the uppermost Formation and the most proximal of the formations. The Moita is dominantly limestone, the Pinda is dolomite, while the Vermelha is siltstone with some carbonate. In the Kwanza and Bengeula Basins the interbedded layers are named, from the base, Quianga, Binga, Tuenza, and Catumbela. The Albian to Cenomanian boundary is a transition from dominantly carbonate sediments to clastic sediments. The transgression over the carbonates begins with the siltstones of the Iabe Formation in the Lower Congo Basin. The Iabe Formation includes the silt and sandstones of the Cenomanian through Maestrichtian. The Kwanza and Benguela Basins have subdivided the Iabe equivalent into several formations. Beginning with the Quissonde which still contains limestone. Above the Quissonde are the Cabo Ledo, Itombe, N'Golome, and Teba Formations. The
Iabe Formation of the Lower Congo Basin is overlain by the Landana Formation deposited during the Paleocene and Eocene. The Landana Formation consists of siltstone with some sand. In the Kwanza and Benguela Basins, the Rio Dande, Gratidao, and the Cunga Formations represent the Paleocene/Eocene deposit of marls and siltstones. Above the Lower Congo Landana Formation is the Malembo sandstone and siltstone. The Malembo Formation represents the Oligocene and Miocene. The Kwanza and Benguela equivalent are the Quifangondo, Luanda, Quenquela Este, and Bento Formations of shales, sandstones, and interbedded dolomites. The Plio-Pleistocene of the Lower Congo Basin is the Cirques Formation. This formation consists of sand and silt. The Kwanza and Benguela Basins are topped by the Quelo Formation of sand and shales (Brognon and Verrier, 1966; Schlumberger, 1991; Ala and Selley, 1997; and Marton et al., 2000).
CHAPTER 3 - ANGOLAN SEQUENCE STRATIGRAPHIC FRAMEWORK

3.1 Angolan Basins

The sequence stratigraphic framework of the offshore Angolan basins is based on interpretation of 2-dimensional regional reflection seismic lines. The seismic data grid consists of twelve dip lines and four strike lines (Figure 3.1). This study focuses on the post-salt section and identifies four major sequences in the post-salt section. The post-salt sediments span from Albian to the present. The ages of these major sequences is estimated from seismic correlations with DSDP well information from the Benguela Basin (Bolli and Ryan, 1978) and published sections from the shelf region of the Lower Congo and Kwanza Basins (Platt et al., 1993; Spathopoulos, 1996; Mauduit et al., 1997; Cole et al., 2000; and Marton et al., 2000).

Several seismic sections are displayed in figures in this chapter to illustrate the sequences and their boundaries. The locations of these seismic sections are noted on the line drawings of figures 3.2 – 3.4. Uninterpreted sections are displayed in figures 3.5 – 3.20.

The four major sequences can be interpreted and correlated throughout each of the three basins and between the basins. The four sequences are labeled on the three Lower Congo Basin dip profiles, the five Kwanza Basin dip profiles, the four Benguela Basin dip profiles, and the four regional strike profiles (Figures 3.21 – 3.23). Additional sequences
Figure 3.1: The location of the seismic reflection data grid used in this study is displayed as heavy black lines. The seismic lines are labeled as Lower Congo Basin lines (LC 1, LC 2, and LC 3), Kwanza Basin lines (K 1, K 2, K 3, K 4, and K 5), Benguela Basin lines (B 1, B 2, B 3, and B 4), and strike lines (S 1, S 2, S 3, and S 4). The location of the DSDP site 364 is noted by a red dot. The map is the bathymetry/topography of the Angolan segment of the South Atlantic region based on satellite data, adapted from Sandwell and Smith (1997) (Marton et al, 2000).
Figure 3.2: Locations of seismic sections of the Lower Congo Basin displayed in figures 3.1 are marked by black boxes. The numbers above the boxes correspond to figure numbers used in this chapter. The locations of the line drawings (LC 2 and LC 3) are shown on figure 3.1.
Kongo Basin displayed in figures in this chapter. The seismic sections are outlined and to figure numbers used in this chapter. The number 5 refers to figure 3.5. Shown on figure 3.1.
Figure 3.3: Locations of seismic sections of the Kwanza Basin displayed in figures in this chapter are shown in black boxes. The numbers above the boxes correspond to figure numbers used in this chapter. The locations of the line drawings (K2 and K4) are shown on figure 3.1.
Basin displayed in figures in this chapter. The seismic sections are outlined by number of figure numbers used in this chapter. The number 10 refers to figure 3.10. See on figure 3.1.
Figure 3.4: Locations of seismic sections of the Benguela Basin displayed in figures in black boxes. The numbers above the boxes correspond to figure numbers used in the text. The locations of the line drawings (B 2 and B 4) are shown on figure 3.1.
The seismic sections are outlined by numbers that correspond to figure numbers used in this chapter. The number 15 refers to figure 3.15, and these numbers are shown on figure 3.1.
Figure 3.5: Uninterpreted seismic section of line LC 2 in the Lower Congo Basin. The location of the section is shown on figure 3.2. An interpretation of the section is displayed in figure 3.92.
Figure 3.6: Uninterpreted seismic section of line LC 3 in the Lower Congo Basin. The location of the section is shown on figure 3.2. Interpretation of the section is included in figures 3.36, 3.76, and 3.89.
Figure 3.7: Uninterpreted seismic section of line LC 3 in the Lower Congo Basin. The location of the section is shown on figure 3.2. Interpretation of the section is included in figures 3.33, 3.41, 3.55, 3.69, and 3.79.
Figure 3.8: Uninterpreted seismic section of line LC 3 in the Lower Congo Basin. The location of the section is shown on figure 3.2. Interpretation of the section is included in figures 3.46, 3.48, and 3.86.
Figure 3.9: Uninterpreted seismic section of line LC 3 in the Lower Congo Basin. The location of the section is shown on figure 3.2. Interpretation of the section is included in figures 3.80 and 3.83.
Figure 3.10: Uninterpreted seismic section of line K 2 in the Kwanza Basin. The location of the section is shown on figure 3.3. An interpretation of the section is displayed in figure 3.93.
Figure 3.11: Uninterpreted seismic section of line K 4 in the Kwanza Basin. The location of the section is shown on figure 3.3. Interpretation of the section is included in figures 3.28, 3.37, 3.60, 3.65, 3.73, 3.77, and 3.84.
Figure 3.12: Uninterpreted seismic section of line K 4 in the Kwanza Basin. The location of the section is shown on figure 3.3. Interpretation of the section is included in figures 3.31, 3.40, 3.63, 3.66, 3.72, and 3.88.
Figure 3.13: Uninterpreted seismic section of line K 4 in the Kwanza Basin. The location of the section is shown on figure 3.3. Interpretation of the section is included in figures 3.50, 3.62, 3.70, and 3.82.
Figure 3.14: Uninterpreted seismic section of line K 4 in the Kwanza Basin. The location of the section is shown on figure 3.3. Interpretation of the section is included in figures 3.29, 3.38, 3.42, 3.47, 3.49, 3.53, 3.58, 3.61, 3.64, and 3.91.
Figure 3.15: Uninterpreted seismic section of line B 2 in the Benguela Basin. The location of the section is shown on figure 3.4. An interpretation of the section is displayed in figure 3.94.
Figure 3.16: Uninterpreted seismic section of line B 4 in the Benguela Basin. The location of the section is shown on figure 3.4. Interpretation of the section is included in figures 3.30, 3.35, 3.45, 3.57, 3.71, 3.74, 3.78, and 3.90.
Figure 3.17: Uninterpreted seismic section of line B 4 in the Benguela Basin. The location of the section is shown on figure 3.4. Interpretation of the section is included in figures 3.44, 3.51, 3.56, 3.67, 3.68, 3.85, and 3.87.
Figure 3.18: Uninterpreted seismic section of line B 4 in the Benguela Basin. The location of the section is shown on figure 3.4. Interpretation of the section is included in figures 3.39 and 3.81.
Figure 3.19: Uninterpreted seismic section of line B 4 in the Benguela Basin. The location of the section is shown on figure 3.4. Interpretation of the section is included in figure 3.34.
Figure 3.20: Uninterpreted seismic section of line B 4 in the Benguela Basin. The location of the section is shown on figure 3.4. Interpretation of the section is included in figures 3.32, 3.52, and 3.54.
Figure 3.21: Line drawings of three Lower Congo Basin reflection seismic lines (LC 1, LC 2, and LC 3). Salt, major sequence boundaries (SB1, SB2, and SB3), and the sea floor are thick black lines. Also thick black lines. The vertical scale is in seconds TWT and the horizontal scale is in kilometers.
Figure 3.1 shows the location of certain seismic lines (LC 1, LC 2, and LC 3). The base of salt, top of sea floor are thick black lines. Lower order sequence boundaries are thin black lines. Faults are marked, and the horizontal scale is in kilometers.
Figure 3.22: Line drawings of five Kwanza Basin reflection seismic lines (K1, K2, K3, K4, and K5), major sequence boundaries (SB1, SB2, and SB3), and the sea floor are thick black lines. Lower thick black lines. The vertical scale is in seconds TWT and the horizontal scale is in kilometers.
Horizontal lines (K1, K2, K3, K4, and K5). Locations shown on figure 3.1. The base of salt, top of salt, horizon are thick black lines. Lower order sequence boundaries are thin black lines. Faults are also shown.
Figure 3.23: Line drawings of four Benguela Basin reflection seismic lines (B 1, B 2, B 3, and B 4), showing sequence boundaries (SB1, SB2, and SB3), and the seafloor is thick black lines. The location of DSDP site 364 is projected onto the line drawing. The vertical scale is 2 s (TWT) and the horizontal scale is 15 Km.
isic lines (B 1, B 2, B 3, and B 4). Locations shown on figure 3.1. The base of salt, top of salt, major are thick black lines. Lower order sequence boundaries are thin black lines. Faults are also thick black drawing. The vertical scale is in seconds TWT and the horizontal scale is in kilometers.
are identified in each of the basins, but can not be correlated regionally across the offshore basins.

The timing of the major sequences is estimated by correlating the interpreted seismic sequences with ages in the DSDP wells (Figures 3.24 and 3.25) and in shelf sections. The published ages have a wide range. Each of the interpreted major seismic sequence boundaries has an age range that includes a major sequence boundary as published in Hardenbol et al. (1998). It is inferred that the interpreted major sequence boundaries correlate with a major sequence boundary of Hardenbol et al. (1998).

The oldest major sequence deposited over the Aptian salt spans from the end of the Aptian (112.2 +/- 1.1 Ma) to the Turonian (90.0 +/- 0.5 Ma). The second post-salt major sequence was deposited between the Turonian and the end of the Rupelian (30.0 Ma). The third major sequence ranges between the Chattian and Tortonian (10.5 Ma). The fourth, most recent, sequence began in the Tortonian and continues to the present.

The three major sequence boundaries separating the four sequences are correlated with major sequence boundaries found around the world (Hardenbol et al., 1998; Haq et al., 1988; and Vail et al., 1977). The oldest post-salt major sequence boundary is correlated with a major Late Cretaceous sequence boundary, the Tu3. The Tu3 occurs during the Turonian stage and is dated as 90.0 Ma. The second major sequence boundary is matched with the middle Oligocene major sequence boundary, the Ru4/Ch1. The
Figure 3.24: The Deep Sea Drilling Program (DSDP) acquired seismic and core at site 364 in the Benguela Basin. Bolli and Ryan 1978 interprets three unconformities (U1, U2, and U3) bounding four sequences (I, II, III, and IV). The boundaries are noted on the stratigraphic column and the seismic section. One of the Benguela basin seismic lines in this study is very close to site 364. Using the seismic sections, the DSDP unconformities are correlated with the sequence boundaries of this study (SB1, SB2, and SB3). The relation of SB 1, SB 2, and SB 3 to the stratigraphic column of the DSDP 364 core is displayed. Figure 3.6 shows the relation of the DSDP site to the line drawing of the closest seismic profile. (modified from Bolli and Ryan, 1978)
Figure 3.25: Correlation of the DSDP site 364 with seismic line B 2 of the Benguela Basin. The DSDP seismic profile and the position of the site 364 wellbore is shown in the upper right (Bolli, Ryan, et al, 1978). The unconformities interpreted by the shipboard scientific party are correlated to the major sequence boundaries of this study (SB 1, SB 2, and SB 3). The position of the site 364 wellbore is projected onto the line drawing of B 2 in the upper right. The line drawing of the entire profile is shown along the bottom of the figure with a box outlining the enlarged area.
Ru4/Ch1 occurs at the boundary of the Rupelian and Chattian stages at 30.0 Ma. The most recent major sequence boundary is the major Late Miocene sequence boundary, the Ser4/ Tor1. The Ser4/Tor1 occurs during the beginning of the Tortonian stage at 10.5 Ma. Within the major sequence boundaries, other additional sequences are interpreted. The other sequence boundaries cannot be correlated with the same high degree of confidence as the major sequence boundaries and vary between the three Angolan basins. Figure 3.26 is a chart of the sequence boundaries and their assigned ages in the Angolan basins.

3.2 Major sequence 1

Major sequence 1 (MS 1) is the first major sequence deposited over the Aptian salt (Figure 3.26). The timing of MS 1 is correlated as spanning from the Albian to Turonian stage, about 20 Ma. The sequence is defined above and below by unconformities and their correlative conformities. MS 1 is identified in each of the three basins offshore Angola. On the time seismic sections, MS 1 has a thickness of over one second (two-way travel time). The thickness of the sequence varies with deposits as thick as 2 kilometers.

MS 1 thickens from north to south (Figure 3.27). In the Lower Congo Basin, MS 1 does not exceed 500 meters in thickness. Moving to the south, MS 1 is up to 2/3 seconds TWT (1 kilometer thick) in the Kwanza Basin. In the southernmost Angolan basin, Benguela, MS 1 reaches its maximum time of 1.3 seconds TWT (2 kilometers.) As it
<table>
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Figure 3.26: Diagram of the sequence boundaries in each of the offshore Angolan basins. The major sequence boundaries (SB 1, SB 2, and SB 3) are thick lines and interpreted in each basin. The other sequence boundaries are thin black lines. These boundaries can be correlated with confidence within a basin, but not between basins. The dates to the left of the diagram are the interpreted ages of the boundaries. Note that the time scale is not linear.
Figure 3.27: Major sequence 1 (MS 1) is highlighted in black on the three line drawings (LC 2, K 3, and B 2) of the Benguela Basin. MS 1 thins northward through the three basins. The vertical scale is in seconds. The locations of the line drawings (LC 2, K 3, and B 2) are shown on figure 3.1.
on the three line drawings (LC 2, K 3, and B 2). The thickest deposits of MS 1 are found in basins. The vertical scale is in seconds TWT and the horizontal scale is in kilometers. The on figure 3.1.
should if the opening of the South Atlantic advances from south to north and the base of the sequence gets younger.

In general, the thickest MS 1 deposits occur beneath the current shelf and slope (Figure 3.28). The majority of MS 1 deposits were shelf carbonates and pelagic material. During the Albian to Cenomanian stages, carbonate production dominated the shelf environment. Carbonate production created thick carbonate deposits along the paleo-shelf and upper slope. Subsequent movement of the deposits due to salt tectonics, broke the sequence laterally into rafts and moved them basinward to their current position. MS 1 thins basinward and landward of these thick accumulations (Figures 3.29 and 3.30).

The base of MS 1 is clearly defined over most of the offshore Angola region (Figure 3.31). The reflector at the base of MS 1 is very strong because of the contrast between the underlying salt and the overlying sediments. The salt has an average internal velocity of 4500 meters/second, while the sediments’ average velocities range between 2100 and 3400 meters/second (Marton et al., 2000). The difference in seismic velocity of the layers creates a strong top of salt/base of MS 1 reflector (Figure 3.32). The definition of the base of MS 1 is also clear because the transition from the salt to the sediments of MS 1 is relatively abrupt and not gradual. Difficulty in defining the base of MS 1 arises in the shallow shelf region. In the shelf region the velocity of the carbonates is close to the velocity of the salt. In these areas the base of MS 1 reflector is not as strong or clear.
Figure 3.28: Major sequence 1 (MS 1), bounded above by sequence boundary 1 and below by the top of salt horizon, is thickest under the current shelf and slope. SB 1 is a thick black line and labeled as ‘SB 1.’ The top of salt horizon is the thick black line below SB 1. On this seismic profile the top and base of salt horizons amalgamate. Note that MS 1 is over 1/2 seconds (TWT) thick. This seismic section is from the Kwanza Basin, profile K 4. The location of the section is shown on figure 3.3. An uninterpreted section is provided in figure 3.11.
Figure 3.29: Major sequence 1 (MS 1), bounded above by sequence boundary 1 and below by the top of salt horizon, thins basinward. SB 1 is a thick black line and labeled as ‘SB 1.’ The top of salt horizon is the thick black line below SB 1. Note that MS 1 is only 1/3 seconds (TWT) thick in this distal section compared to 1/2 seconds (TWT) thickness in figure 3.28 updip. The location of the seismic section is from the Kwanza Basin, profile K 4. The location of the section is shown on figure 3.3. An uninterpreted section is provided in figure 3.14.
Figure 3.30: Major sequence 1 (MS 1), bounded above by sequence boundary 1 and below by the top of salt horizon, thins landward. SB 1 is a thick black line and labeled as ‘SB 1.’ The top of salt horizon is the thick black line below SB 1. Note that MS 1 is only 1/4 to 1/3 seconds (TWT) thick in this section compared to 1/2 seconds (TWT) thickness in figure 3.28. The location of the seismic section is from the Benguela Basin, profile B 4. The location of the section is shown on figure 3.4. An uninterpreted section is provided in figure 3.16.
Figure 3.31: The base of major sequence 1 (MS 1) is clearly defined offshore Angola. The base of MS 1 is the thick black line below the line labeled as 'SB 1. The base of MS 1 is the top of salt horizon which can amalgamate with the base of salt horizon, as in this section. The location of the seismic section is from the Kwanza Basin, profile K 4. The location of the section is shown on figure 3.3. An uninterpreted section is provided in figure 3.12.
Figure 3.32: The base of major sequence 1 (MS 1) is a strong reflector. The base of MS 1 is noted by arrows. Notice the large amplitude of the base of MS 1 reflector on the western (left) side of the figure. The seismic velocity contrast between the sediment and the salt provides the strong reflection. To the east (right), a horizontal arrow points to a group of strong reflectors. Several reflectors represent the base of MS 1 in this minibasin because the 2D imaging is not able to account for out-of-plane effects of neighboring salt bodies. The location of the seismic section is from the Benguela Basin, profile B 4. The location of the section is shown on figure 3.4. An uninterpreted section is provided in figure 3.20.
The seismic character of MS 1 is similar across the basins from north to south. The reflectors within the sequence are both strong and widely spaced vertically (Figures 3.33 and 3.34). Beneath the current shelf and upper slope, the reflectors of MS 1 are chaotic. Due to the movement of the salt, the deposits are faulted and rotated. The salt movement occurred syndepositionally in the latter part of the sequence. The salt tectonics also occurred postdepositionally during deposition of the entire sequence. The eastern, or landward, portion of MS 1 contains rotated reflectors, as well as onlap and truncation terminations of reflectors (Figure 3.35). The general appearance on regional seismic lines of the shallow portion of MS 1 is chaotic (Figures 3.36 and 3.37). Moving basinward, the reflectors become concordant. The reflectors in the upper portion of MS 1 are strong and have ‘railroad track’ character (Figures 3.38 and 3.39). The lower reflectors are faded in areas. The faded appearance of these reflectors can be attributed to distortion of seismic energy by neighboring salt bodies, both in and out of the plane of the 2-dimensional seismic line.

MS 1 is subdivided into two sequences on most of the seismic profiles (Figure 3.40). The separation of upper and lower sequences within MS 1 can not be correlated between the basins with the same confidence as the three major sequence boundaries. The sequence boundary within MS 1 does appear to be significant, but not on the same scale as the MS 1’s boundaries. This internal sequence boundary has been correlated with the DSDP data of site 364 and dated as late Albian, possibly the 99 or 98 Ma medium sequence boundary of Hardenbol et al. (1998).
Figure 3.33: Reflectors within major sequence 1 (MS 1), bounded above by sequence boundary 1 and below by the top of salt horizon, are strong and widely spaced. SB 1 is a thick black line and labeled as ‘SB 1.’ The top of salt horizon is the thick black line below SB 1. On this seismic profile the top and base of salt horizons amalgamate in regions. Note the strong and widely spaced (vertically) reflectors near the SB 1 label. This seismic section is from the Lower Congo Basin, profile LC 3. The location of the section is shown on figure 3.2. An uninterpreted section is provided in figure 3.7.
Figure 3.34: Reflectors within major sequence 1 (MS 1), bounded above by sequence boundary 1 and below by the top of salt horizon, are strong and widely spaced. SB 1 is a thick black line and labeled as 'SB 1.' The top of salt horizon is the thick black line below SB 1. On this seismic profile the top and base of salt horizons amalgamate in regions. Note the strong and widely spaced (vertically) reflectors to the west and east of the central salt pillow. This seismic section is from the Benguela Basin, profile B 4. The location of the section is shown on figure 3.4. An uninterpreted section is provided in figure 3.19.
Figure 3.35: Major sequence 1 (MS 1), bounded above by sequence boundary 1 and below by the top of salt horizon, contains rotated reflectors and erosional truncation and onlap terminations. SB 1 is a thick black line and labeled as 'SB 1.' The top of salt horizon is the thick black line below SB 1. On this seismic profile the top and base of salt horizons amalgamate in regions. Note the pattern of reflectors highlighted by black lines within MS 1. This seismic section is from the Benguela Basin, profile B 4. The location of the section is shown on figure 3.4. An uninterpreted section is provided in figure 3.16.
Figure 3.36: Major sequence 1 (MS 1), bounded above by sequence boundary 1 and below by the top of salt horizon, contains chaotic reflectors. SB 1 is a thick black line and labeled as ‘SB 1.’ The top of salt horizon is the thick black line below SB 1. On this seismic profile the top and base of salt horizons amalgamate in regions. Note the chaotic pattern of reflectors within MS 1. This seismic section is from the Lower Congo Basin, profile LC 3. The location of the section is shown on figure 3.2. An uninterpreted section is provided in figure 3.6.
Figure 3.37: Major sequence 1 (MS 1), bounded above by sequence boundary 1 and below by the top of salt horizon, contains chaotic reflectors. SB 1 is a thick black line and labeled as 'SB 1.' The top of salt horizon is the thick black line below SB 1. On this seismic profile the top and base of salt horizons amalgamate in regions. Note the chaotic pattern of reflectors within MS 1 in the western (left) and central portion of this section. The chaotic pattern contrasts with the concordant reflectors seen in the easternmost (right) portion of the section. This seismic section is from the Kwanza Basin, profile K 4. The location of the section is shown on figure 3.3. An uninterpreted section is provided in figure 3.11.
Figure 3.38: Major sequence 1 (MS 1), bounded above by sequence boundary 1 and below by the top of salt horizon, has reflectors that are strong and have 'railroad track' character. SB 1 is a thick black line and labeled as 'SB 1.' The top of salt horizon is the thick black line below SB 1. Note the strong amplitude and concordant character of reflectors within the upper portion of MS 1. This seismic section is from the Kwanza Basin, profile K 4. The location of the section is shown on figure 3.3. An uninterpreted section is provided in figure 3.14.
Figure 3.39: Major sequence 1 (MS 1), bounded above by sequence boundary 1 and below by the top of salt horizon, has reflectors that are strong and have 'railroad track' character. SB 1 is a thick black line and labeled as 'SB 1.' The top of salt horizon is the thick black line below SB 1. Note the strong amplitude and concordant character of reflectors within the upper portion of MS 1. The reflectors are slightly faulted over the crest off the central structure. This seismic section is from the Benguela Basin, profile B 4. The location of the section is shown on figure 3.4. An uninterpreted section is provided in figure 3.18.
Figure 3.40: Major sequence 1 (MS 1), bounded above by sequence boundary 1 and below by the top of salt horizon, is subdivided into two sequences. SB 1 is a thick black line and labeled as 'SB 1.' The sequence boundary separating the lower and upper sequence within MS 1 is the black line below SB 1. The top of salt horizon is the lowest thick black line. This sequence boundary within MS 1 can be correlated within each of the three basins. However, correlation of this boundary between basins can not be done with confidence. This seismic section is from the Kwanza Basin, profile K 4. The location of the section is shown on figure 3.3. An uninterpreted section is provided in figure 3.12.
The top of MS 1 is an unconformity and its correlative conformity. Both erosional truncation and onlap define the unconformity. The termination of MS 1 reflectors below this sequence boundary is characterized by erosional truncation (Figure 3.41). Above the boundary, the reflectors of the overlying sequence terminate onto the surface by onlap. The majority of erosional truncation terminations occur in the eastern portion of the basin, under the current shelf and slope. Onlap of overlying reflectors can be observed throughout the basin (Figure 3.42). Only in the westernmost portion of the basin, close to the abyssal plain, does the sequence boundary lose the onlapping reflectors. At the westernmost extent of the seismic lines, the sequence boundary is the correlative conformity of the unconformity defined to the east.

3.3 Major sequence 2

Major sequence 2 (MS 2) is the second major sequence of the post-salt section (Figure 3.26). MS 2 is correlated to date between the Turonian and Rupelian stages. MS 2 is about 60 My in duration. This Late Cretaceous to middle Oligocene sequence is bounded above and below by unconformities and their correlative conformities. MS 2 is identified in each of the three Angolan basins. In the time domain, MS 2 has a thickness of over one second (two-way travel time). The thickness of the sequence is up to 2 kilometers.

The thickness of MS 2 varies significantly between the basins (Figure 3.43). MS 2 is thickest in the Lower Congo Basin with a thickness of 1.5 seconds TWT (2 kilometers.) In the Kwanza Basin, MS 2 only reaches 3/4 second TWT (1 kilometer) at its maximum
Figure 3.41: The top of major sequence 1 (MS 1) and base of major sequence 2 (MS 2) is sequence boundary 1 (SB 1). SB 1 is a thick black line and labeled as ‘SB 1.’ Below SB 1, reflectors terminate by erosional truncation. The erosional truncation of several reflectors is noted by black lines below SB 1. This seismic section is from the Lower Congo Basin, profile LC 3. The location of the section is shown on figure 3.2. An uninterpreted section is provided in figure 3.12.
Figure 3.42: The top of major sequence 1 (MS 1) and base of major sequence 2 (MS 2) is sequence boundary 1 (SB 1). SB 1 is a thick black line and labeled as ‘SB 1.’ Above SB 1, reflectors terminate by onlap. The onlap of several reflectors is noted by black lines above SB 1. This seismic section is from the Kwanza Basin, profile K 4. The location of the section is shown on figure 3.3. An uninterpreted section is provided in figure 3.14.
Figure 3.43: Major sequence 2 (MS 2) is highlighted in black on the three line drawings (LC 2, K 3, and B 2) of the Lower Congo Basin. MS 2 is thinnest in the Kwanza Basin. The vertical scale is in seconds two-way travel time (TWT). The horizontal scale is in kilometers (Km).
black on the three line drawings (LC 2, K 3, and B 2). The thickest deposits of MS 2 are found in the Basin. The vertical scale is in seconds TWT and the horizontal scale is in kilometers. The shown on figure 3.1.
thickness. Moving farther south, the Benguela Basin MS 2 has a thickness of 1.2 seconds TWT (1.5 kilometers.) The deposits of MS 2 are greatest in the northernmost basin, the Lower Congo. In the Kwanza Basin MS 2 thins, before expanding into the Benguela Basin.

The thickness of MS 2 deposits varies significantly within the basins from east to west (Figure 3.44). MS 2 consists of clastics deposited during the Turonian to Rupelian stages. MS 2 is relatively thin in the shelf region (Figure 3.45). The sequence expands down the slope, where the majority of accommodation space existed during its deposition (Figure 3.46). From the toe of the slope to the western edge of the basin, the sequence varies between 0 and 1.5 seconds TWT (0 - 2 kilometers) thickness. The strong variation in thickness is due to the formation of salt structures. During the deposition of MS 2, these salt structures were substantial enough to affect the deposition of sediments. Sediments flowed around relative highs and ponded into minibasins.

The base of MS 2 is defined over the offshore Angola region. The sequence boundary separating MS 1 and MS 2 is named sequence boundary 1 (SB 1) in this study. SB 1 is an unconformity, defined by both erosional truncation and onlap, and its correlative conformity. Below SB 1, the reflectors of MS 1 terminate by erosional truncation (Figure 3.41). The erosional truncation occurs mainly under the current shelf and slope. Above SB 1, the first reflectors of MS 2 terminate by onlap onto the SB 1 surface (Figure 3.42). Onlap can be identified throughout the basins. Toward the western extent of the seismic
Figure 3.44: Major sequence 2 (MS 2), bounded above by sequence boundary 2 and below by sequence boundary 1, varies in thickness laterally. Sequence boundaries 1 and 2 (SB 1 and SB 2) are thick black lines and labeled as 'SB 1' and 'SB 2.' Note that MS 2 varies between 1/4 and 1 second (TWT) thick over a 20 kilometer distance. This seismic section is from the Benguela Basin, profile B 4. The location of the section is shown on figure 3.4. An uninterpreted section is provided in figure 3.17.
Figure 3.45: Major sequence 2 (MS 2), bounded above by sequence boundary 2 and below by sequence boundary 1, thins in the shelf region. Sequence boundaries 1 and 2 (SB 1 and SB 2) are thick black lines and labeled as 'SB 1' and 'SB 2.' Note that MS 2 varies between 1/4 and 1/2 seconds (TWT) thick in this section. This seismic section is from the Benguela Basin, profile B 4. The location of the section is shown on figure 3.4. An uninterpreted section is provided in figure 3.16.
Figure 3.46: Major sequence 2 (MS 2), bounded above by sequence boundary 2 and below by sequence boundary 1, expands basinward. Sequence boundaries 1 and 2 (SB 1 and SB 2) are thick black lines and labeled as ‘SB 1’ and ‘SB 2.’ Note that MS 2 varies between 1/2 and 1.5 seconds (TWT) thick in this section. This seismic section is from the Lower Congo Basin, profile LC 3. The location of the section is shown on figure 3.2. An uninterpreted section is provided in figure 3.8.
lines, SB 1 transforms from an unconformity to a correlative conformity (Figure 3.47). The transition between MS 1 and MS 2 is not recorded as a strong reflector, because the difference in the average seismic velocities of the sequences is not great (Figure 3.48). The average seismic velocity of MS 1 is 3400 meters/second, while the average velocity of MS 2 is 3200 meters/second (Marton et al., 2000).

The seismic character of MS 2 is similar across the basins from north to south. MS 2 contains a great deal of variety in seismic character. In each of the basins, MS 2 has concordant, divergent, convergent, faulted, and chaotic reflectors. The strength and spacing of the reflectors varies as well. At the eastern and western edges of the basin, the reflectors of MS 2 are relatively concordant (Figure 3.49). In the center of the basin, amidst the salt structures, the reflectors converge toward the salt features and diverge toward the center of minibasins (Figure 3.50). Due to movement of the deposits syn- and post-depositionally with the salt, faults cut the reflectors. Channels and channel complexes, of various scales, can be identified throughout the basins. The reflectors in the channels or channel complexes are chaotic (Figure 3.51). The vertical spacing of the reflectors narrows upward in the sequence (Figure 3.52). The reflectors are thinner at the top of the sequence than at the base. The strength of the reflectors increases vertically in the sequence. The sequence can often be split into a "weaker amplitude", lower section and a "stronger amplitude", upper section (Figure 3.53 and 3.54).
Figure 3.47: Sequence boundary 1, bounding MS 1 and MS 2, is an unconformable surface to the east, but becomes conformable in the western portions of the basins. Sequence boundary 1 is a thick black line and labeled as ‘SB 1.’ In the eastern (right) side of this section, reflectors onlap the unconformable SB 1 (see figure 3.42). On the western (left) side of the SB 1 label, the reflectors above and below the boundary are concordant. This seismic section is from the Kwanza Basin, profile K 4. The location of the section is shown on figure 3.3. An uninterpreted section is provided in figure 3.14.
Figure 3.48: Sequence boundary 1, bounding MS 1 and MS 2, is not recorded as a strong reflector. Sequence boundary 1 is noted by arrows. The seismic velocity contrast between the sediments of MS 1 and MS 2 is small, therefore the reflection does not have a large amplitude. This seismic section is from the Lower Congo Basin, profile LC 3. The location of the section is shown on figure 3.2. An uninterpreted section is provided in figure 3.8.
Figure 3.49: Major sequence 2 (MS 2), bounded above by sequence boundary 2 and below by sequence boundary 1, contains concordant reflectors. Sequence boundaries 1 and 2 (SB 1 and SB 2) are thick black lines and labeled as ‘SB 1’ and ‘SB 2.’ Note the relative concordance of the MS 2 reflectors across this section. This seismic section is from the Kwanza Basin, profile K 4. The location of the section is shown on figure 3.3. An uninterpreted section is provided in figure 3.14.
Figure 3.50: Major sequence 2 (MS 2), bounded above by sequence boundary 2 and below by sequence boundary 1, contains converging and diverging reflectors. Sequence boundaries 1 and 2 (SB 1 and SB 2) are thick black lines and labeled as ‘SB 1’ and ‘SB 2.’ Note that the reflectors within MS 2 diverge into minibasins and converge over salt structures. This seismic section is from the Kwanza Basin, profile K 4. The location of the section is shown on figure 3.3. An uninterpreted section is provided in figure 3.13.
Figure 3.51: Major sequence 2 (MS 2), bounded above by sequence boundary 2 and below by sequence boundary 1, contains patches of chaotic reflectors. Sequence boundaries 1 and 2 (SB 1 and SB 2) are thick black lines and labeled as 'SB 1' and 'SB 2.' Note the chaotic pattern of reflectors that occurs in patches within MS 2. These chaotic areas may be channel complexes. This seismic section is from the Benguela Basin, profile B 4. The location of the section is shown on figure 3.4. An uninterpreted section is provided in figure 3.17.
Figure 3.52: Reflectors within major sequence 2 (MS 2), bounded above by sequence boundary 2 and below by sequence boundary 1, narrow upward in the sequence. Sequence boundaries 1 and 2 (SB 1 and SB 2) are thick black lines and labeled as ‘SB 1’ and ‘SB 2.’ Note the narrowing of the reflector spacing between the SB 1 and SB 2 labels. This seismic section is from the Benguela Basin, profile B 4. The location of the section is shown on figure 3.4. An uninterpreted section is provided in figure 3.20.
Figure 3.53: Major sequence 2 (MS 2), bounded above by sequence boundary 2 and below by sequence boundary 1, can be split into a "weaker amplitude," lower section and a "stronger amplitude," upper section. Sequence boundaries 1 and 2 (SB 1 and SB 2) are thick black lines and labeled as 'SB 1' and 'SB 2.' The lower portion of MS 2 has a faded character, while the upper portion has strongly defined reflectors. This seismic section is from the Kwanza Basin, profile K 4. The location of the section is shown on figure 3.3. An uninterpreted section is provided in figure 3.14.
Figure 3.54: Major sequence 2 (MS 2), bounded above by sequence boundary 2 and below by sequence boundary 1, can be split into a "weaker amplitude," lower section and a "stronger amplitude," upper section. Sequence boundaries 1 and 2 (SB 1 and SB 2) are thick black lines and labeled as 'SB 1' and 'SB 2.' The lower portion of MS 2 has a faded character, while the upper portion has strongly defined reflectors. The difference between the two sections is most visible in the western (left) minibasin. This seismic section is from the Benguela Basin, profile B 4. The location of the section is shown on figure 3.4. An uninterpreted section is provided in figure 3.20.
MS 2 can be split into three medium sequences in each of the three basins (Figures 3.55 and 3.56). However, these medium sequences can not be correlated with the same confidence as the major sequences between the basins. The two sequence boundaries separating the three sequences within MS 2 could not be directly dated. Five likely candidates for these boundaries are 39.5, 49.5, 58.5, 68, and 80 Ma. These probable dates are based on the major sequence boundaries noted by Hardenbol et al. (1998) within MS 2, between 90 and 30 Ma.

The top of MS 2 is a striking unconformity and its correlative conformity. This sequence boundary (SB 2) is the most obvious unconformity in the post-salt section. The unconformity is erosive throughout the whole offshore Angola area, terminating reflectors of MS 2 by erosional truncation (Figure 3.57). Even more striking than the erosion is the degree of onlap by reflectors of the overlying sequence onto SB 2 (Figure 3.58). The onlap suggests extensive movement and rotation of the MS 2 deposits, during a time of submarine erosion and non-deposition. The next deposits had large accommodation spaces to fill, onlapping long stretches of SB 2. Due to the extent of erosional truncation and onlap, SB 2 could be correlated with a high degree of confidence throughout and between the Angolan basins.

3.4 Major sequence 3

Major sequence 3 (MS 3) is the third major sequence of the post-salt section (Figure 3.26). MS 3 spans from the Chattian to Tortonian stage, or about 10 My. This middle
Figure 3.55: Major sequence 2 (MS 2), bounded above by sequence boundary 2 and below by sequence boundary 1, is subdivided into three sequences. Sequence boundaries 1 and 2 are thick black lines and labeled as 'SB 1' and 'SB 2.' The sequence boundaries separating the sequences within MS 2 are the black lines between SB 1 and SB 2. These sequence boundaries within MS 2 can be correlated within each of the three basins. However, correlation of the two boundaries between basins can not be done with confidence. This seismic section is from the Lower Congo Basin, profile LC 3. The location of the section is shown on figure 3.2. An uninterpreted section is provided in figure 3.7.
Figure 3.56: Major sequence 2 (MS 2), bounded above by sequence boundary 2 and below by sequence boundary 1, is subdivided into three sequences. Sequence boundaries 1 and 2 are thick black lines and labeled as 'SB 1' and 'SB 2.' The sequence boundaries separating the sequences within MS 2 are the black lines between SB 1 and SB 2. These sequence boundaries within MS 2 can be correlated within each of the three basins. However, correlation of the two boundaries between basins can not be done with confidence. This seismic section is from the Benguela Basin, profile B 4. The location of the section is shown on figure 3.4. An uninterpreted section is provided in figure 3.17.
Figure 3.57: The top of major sequence 2 (MS 2) and base of major sequence 3 (MS 3) is sequence boundary 2 (SB 2). SB 2 is a thick black line and labeled as ‘SB 2.’ Below SB 2, reflectors terminate by erosional truncation. The erosional truncation of several reflectors is noted by black lines below SB 2. This seismic section is from the Benguela Basin, profile B 4. The location of the section is shown on figure 3.4. An uninterpreted section is provided in figure 3.16.
Figure 3.58: The top of major sequence 2 (MS 2) and base of major sequence 3 (MS 3) is sequence boundary 2 (SB 2). SB 2 is a thick black line and labeled as ‘SB 2.’ Above SB 2, reflectors terminate by onlap. The onlap of several reflectors is noted by black lines above SB 2. This seismic section is from the Kwanza Basin, profile K 4. The location of the section is shown on figure 3.3. An uninterpreted section is provided in figure 3.14.
Oligocene to Late Miocene sequence is defined above and below by unconformities and their correlative conformities. MS 3 has been correlated throughout and between the three Angolan basins. On a seismic time profile, MS 3 reaches thicknesses of over one second (two-way travel time). The sequence is up to 2.5 kilometers thick.

The thickness of MS 3 varies significantly between the basins (Figure 3.59). As with MS 2, MS 3 is thicker in the Lower Congo and Benguela Basins than in the Kwanza Basin. In the Lower Congo Basin, MS 3 is up to 1.1 seconds TWT (2.5 kilometers) thick. Moving southward into the Kwanza Basin, MS 3 is at most 1/2 seconds TWT (1 kilometer) thick. Farther south in the Benguela Basin, MS 3 is expanded again to thicknesses up to 3/4 second TWT (2 kilometers.) The thickest layers are formed in the Lower Congo Basin during MS 3, the next thickest layers are in the Benguela Basin, while the central Kwanza Basin has the thinnest layers.

The thickness of MS 3 deposits changes from east to west within each of the basins. The deposits of MS 3 are Chattian to Tortonian clastic sediments. In the east, the MS 3 deposits are thick relative to the two earlier post-salt major sequences, MS 1 and MS 2. MS 3 remains thick under the present shelf and slope (Figure 3.60). The sequence gradually thins westward across the basin (Figure 3.61). As in MS 2, the deposits of MS 3 are affected by the salt structures. Since the sediments are diverted around the salt structures and into the adjacent minibasins. MS 3 thins toward and over salt structures
Figure 3.59: Major sequence 3 (MS 3) is highlighted in black on the three line drawings (LC 2, K 3, and B 2) of the Lower Congo Basin. MS 3 is thinnest in the Kwanza Basin. The vertical scale is in seconds TWT. The locations of the line drawings (LC 2, K 3, and B 2) are shown on figure 3.1.
In the three line drawings (LC 2, K 3, and B 2). The thickest deposits of MS 3 are found in ... The vertical scale is in seconds TWT and the horizontal scale is in kilometers. The explanation is on figure 3.1.
Figure 3.60: Major sequence 3 (MS 3), bounded above by sequence boundary 3 and below by sequence boundary 2, is thick under the present shelf and slope. Sequence boundaries 2 and 3 (SB 2 and SB 3) are thick black lines and labeled as ‘SB 2’ and ‘SB 3.’ Note that MS 3 varies between 1 and 2 seconds (TWT) thick in this section. This seismic section is from the Kwanza Basin, profile K 4. The location of the section is shown on figure 3.3. An uninterpreted section is provided in figure 3.11.
Figure 3.61: Major sequence 3 (MS 3), bounded above by sequence boundary 3 and below by sequence boundary 2, thins basinward. Sequence boundaries 2 and 3 (SB 2 and SB 3) are thick black lines and labeled as 'SB 2' and 'SB 3.' Note that MS 3 is less than 1/2 seconds (TWT) thick across this section as compared to 2 seconds (TWT) thick updip (Figure 3.60). This seismic section is from the Kwanza Basin, profile K 4. The location of the section is shown on figure 3.3. An uninterpreted section is provided in figure 3.14.
and thickens into the centers of minibasins (Figure 3.62). Variations in thickness are used to determine the existence of paleo-salt structures that have since deflated.

The base of MS 3 is easily defined throughout the basins of offshore Angola. The sequence boundary, SB 2, separating MS 2 and MS 3 is a striking unconformity and its correlative conformity. Throughout each basin, the reflectors below SB 2 terminate by erosional truncation (Figure 3.57). Above SB 2, the reflectors of MS 3 onlap the boundary (Figure 3.58). This onlap is striking and present across the entire basin and margin. During the hiatus between the final deposition of MS 2 and initial deposition of MS 3, extensive submarine erosion and movement occurred. First the top of MS 2 was eroded, creating the erosional truncation on the seismic profiles. Then, during the erosion and non-deposition, the basin overall deepened and the individual minibasins deepened. With the accommodation space increased so drastically, the initial sediments of MS 3 had to onlap SB 2 over large areas. SB 2 is also easily defined because it has a strong amplitude (Figure 3.63). The average seismic velocity of MS 2 is 3200 meters/second, while MS 3’s is 2300 meters/second (Marton et al., 2000). This difference in seismic velocity creates a strong reflection.

The internal nature of MS 3 changes significantly within the basins. MS 3 contains concordant, divergent, convergent, faulted, and chaotic reflectors. The reflectors are concordant along some of the slope profiles and at the western edges of the basins. Reflectors diverge and converge between minibasins and salt structures (Figure 3.64).
Figure 3.62: Major sequence 3 (MS 3), bounded above by sequence boundary 3 and below by sequence boundary 2, thickens and thins in minibasins. Sequence boundaries 2 and 3 (SB 2 and SB 3) are thick black lines and labeled as ‘SB 2’ and ‘SB 3.’ Note that MS 3 thickens toward the center of minibasins and thins toward and over salt structures. This seismic section is from the Kwanza Basin, profile K 4. The location of the section is shown on figure 3.3. An uninterpreted section is provided in figure 3.13.
Figure 3.63: Sequence boundary 2, bounding MS 2 and MS 3, is easily defined and has a strong amplitude. Sequence boundary 2 is noted by arrows. Due to the seismic velocity contrast between the sediments of MS 2 and MS 3, the reflection has a large amplitude. This seismic section is from the Kwanza Basin, profile K 4. The location of the section is shown on figure 3.3. An uninterpreted section is provided in figure 3.12.
Figure 3.64: Major sequence 3 (MS 3), bounded above by sequence boundary 3 and below by sequence boundary 2, contains converging and diverging reflectors. Sequence boundaries 2 and 3 (SB 2 and SB 3) are thick black lines and labeled as 'SB 2' and 'SB 3.' Note that the reflectors within MS 3 diverge into minibasins and converge over salt structures. Notice that MS 3 is not influenced by the same frequency of minibasins as MS 2 is influenced by. This seismic section is from the Kwanza Basin, profile K 4. The location of the section is shown on figure 3.3. An uninterpreted section is provided in figure 3.14.
MS 3 is strongly faulted in the shelf and slope region (Figure 3.65). A few faults disrupt the MS 3 reflectors deeper in the basins. Large areas of reflectors are chaotic (Figure 3.66). These chaotic reflectors are interpreted as channels and large channel complexes. The spacing of reflectors in MS 3 is narrower than in both MS 1 and MS 2. The reflectors of MS 3 are generally thin. The strength of the MS 3 reflectors varies both vertically and laterally (Figure 3.67).

MS 3 can be subdivided into at least three sequences in each of the three Angolan basins. In the Benguela Basin, five sequences within MS 3 can be correlated with confidence around the basin (Figure 3.68). While in the Lower Congo and Kwanza Basins, MS 3 can only be separated into three sequences with any confidence (Figures 3.69 and 3.70). The one of the two sequence boundaries that is identified in each of the basins within MS 3 may be the 21 Ma major sequence boundary of Hardenbol et al. (1998). The other three boundaries may correlate with the 15.5, 16.5, and 25.5 Ma medium sequence boundaries of Hardenbol et al. (1998).

The top of MS 3 is an unconformity and its correlative conformity. The unconformity is defined by both erosional truncation and onlap. The top of MS 3 is labeled as sequence boundary 3, SB 3. Reflectors of MS 3 terminate by erosional truncation under SB 3 (Figure 3.71). This erosion is seen throughout the basins, although it is not as much as that of SB 2. The onlap of reflectors above SB 3 is also visible throughout the basins (Figure 3.72). The hiatus between MS 3 and the overlying sequence did not create as
Figure 3.65: Major sequence 3 (MS 3), bounded above by sequence boundary 3 and below by sequence boundary 2, is heavily faulted in the shelf and slope region. Sequence boundaries 2 and 3 (SB 2 and SB 3) are thick black lines and labeled as 'SB 2' and 'SB 3.' Note the high frequency of faults in MS 3 in this shelf region. This seismic section is from the Kwanza Basin, profile K 4. The location of the section is shown on figure 3.3. An uninterpreted section is provided in figure 3.11.
Figure 3.66: Major sequence 3 (MS 3), bounded above by sequence boundary 3 and below by sequence boundary 2, contains patches of chaotic reflectors. Sequence boundaries 2 and 3 (SB 2 and SB 3) are thick black lines and labeled as 'SB 2' and 'SB 3.' Note the chaotic pattern of reflectors that occurs in patches within MS 3. The chaotic pattern is particularly clear in the eastern (right) side of the section under the SB 3 label. These chaotic areas may be channel complexes. This seismic section is from the Kwanza Basin, profile K 4. The location of the section is shown on figure 3.3. An uninterpreted section is provided in figure 3.12.
Figure 3.67: Reflectors within major sequence 3 (MS 3), bounded above by sequence boundary 3 and below by sequence boundary 2, vary in amplitude laterally. Sequence boundaries 2 and 3 (SB 2 and SB 3) are thick black lines and labeled as ‘SB 2’ and ‘SB 3.’ Note the variable in the amplitude of the reflectors across the seismic section. This seismic section is from the Benguela Basin, profile B 4. The location of the section is shown on figure 3.4. An uninterpreted section is provided in figure 3.17.
Figure 3.68: Major sequence 3 (MS 3), bounded above by sequence boundary 3 and below by sequence boundary 2, is subdivided into five sequences in the Benguela Basin. Sequence boundaries 2 and 3 are thick black lines and labeled as 'SB 2' and 'SB 3.' The four sequence boundaries separating the sequences within MS 3 are the black lines between SB 2 and SB 3. These sequence boundaries within MS 3 can be correlated within the Benguela Basin. However, the boundaries can not be correlated northward from the Benguela Basin to the Kwanza or Lower Congo Basins. This seismic section is from the Benguela Basin, profile B 4. The location of the section is shown on figure 3.4. An uninterpreted section is provided in figure 3.17.
Figure 3.69: Major sequence 3 (MS 3), bounded above by sequence boundary 3 and below by sequence boundary 2, is subdivided into three sequences in the Lower Congo Basin. Sequence boundaries 2 and 3 are thick black lines and labeled as 'SB 2' and 'SB 3.' The two sequence boundaries separating the sequences within MS 3 are the black lines between SB 2 and SB 3. These sequence boundaries within MS 3 can be correlated within the Lower Congo Basin. However, the boundaries cannot be correlated southward from the Lower Congo Basin to the Kwanza or Benguela Basins. This seismic section is from the Lower Congo Basin, profile LC 3. The location of the section is shown on figure 3.2. An uninterpreted section is provided in figure 3.7.
Figure 3.70: Major sequence 3 (MS 3), bounded above by sequence boundary 3 and below by sequence boundary 2, is subdivided into three sequences in the Kwanza Basin. Sequence boundaries 2 and 3 are thick black lines and labeled as ‘SB 2’ and ‘SB 3.’ The two sequence boundaries separating the sequences within MS 3 are the black lines between SB 2 and SB 3. These sequence boundaries within MS 3 can be correlated within the Kwanza Basin. However, the boundaries can not be correlated from the Kwanza Basin to the Lower Congo or Benguela Basins. This seismic section is from the Kwanza Basin, profile K 4. The location of the section is shown on figure 3.3. An uninterpreted section is provided in figure 3.13.
Figure 3.71: The top of major sequence 3 (MS 3) and base of major sequence 4 (MS 4) is sequence boundary 3 (SB 3). SB 3 is a thick black line and labeled as 'SB 3.' Below SB 3, reflectors terminate by erosional truncation. The erosional truncation of several reflectors is noted by black lines below SB 3. This seismic section is from the Benguela Basin, profile B 4. The location of the section is shown on figure 3.4. An uninterpreted section is provided in figure 3.16.
Figure 3.72: The top of major sequence 3 (MS 3) and base of major sequence 4 (MS 4) is sequence boundary 3 (SB 3). SB 3 is a thick black line and labeled as 'SB 3.' Above SB 3, reflectors terminate by onlap. The onlap of several reflectors is noted by black lines above SB 3. This seismic section is from the Kwanza Basin, profile K 4. The location of the section is shown on figure 3.3. An uninterpreted section is provided in figure 3.12.
much accommodation space as did the hiatus of SB 2. The onlap is therefore not as
dramatic as that of SB 2. Although not as striking as SB 2, SB 3 has erosion and non-
deposition throughout the three basins at the same time. On the majority of profiles, SB 3
amalgamates with the present seafloor. Along the present shelf, MS 3 is exposed. The
reflectors of MS 3 are erosionally truncated at the seafloor (Figures 3.73 and 3.74).

3.5 Major sequence 4

Major sequence 4 (MS 4) is the most recent major sequence in the Angolan basins
(Figure 3.26). MS 4 is correlated as beginning in the Tortonian stage and continuing to
the present. The Late Miocene to Recent sequence is about 10 My long. MS 4 is
bounded below by an unconformity and its correlative conformity and above by the
seafloor. The sequence is present throughout the three basins offshore Angola. MS 4 is
up to profiles over one second (two-way travel time) on seismic time sections and 2.5
kilometers thick on depth converted.

Between the three basins, the thickness of MS 4 changes greatly (Figure 3.75). Similar to
MS 2 and 3, MS 4 is thinner in the Kwanza Basin than in the Lower Congo and Benguela
Basins. MS 4 is up to 1.2 seconds TWT (2.5 kilometers) in the Lower Congo Basin. In
the Kwanza Basin, MS 4 is the thinnest with 1/2 second TWT (1 kilometer.) In the
Benguela Basin, MS 4 has a maximum thickness of 1 second TWT (2 kilometers.) As
with the two major sequences below it, MS 4 has its thickest deposits in the Lower
Figure 3.73: Major sequence 3 (MS 3), bounded above by sequence boundary 3 and below by sequence boundary 2, is exposed at the seafloor on the eastern portion of the shelf. Sequence boundaries 2 and 3 (SB 2 and SB 3) are thick black lines and labeled as 'SB 2' and 'SB 3.' On the eastern (right) side of the section, the reflectors of MS 3 terminate by erosional truncation at the seafloor. This seismic section is from the Kwanza Basin, profile K 4. The location of the section is shown on figure 3.3. An uninterpreted section is provided in figure 3.11.
Figure 3.74: Major sequence 3 (MS 3), bounded above by sequence boundary 3 and below by sequence boundary 2, is exposed at the seafloor on the eastern portion of the shelf. Sequence boundaries 2 and 3 (SB 2 and SB 3) are thick black lines and labeled as ‘SB 2’ and ‘SB 3.’ On the eastern (right) side of the section, the reflectors of MS 3 terminate by erosional truncation at the seafloor. This seismic section is from the Benguela Basin, profile B 4. The location of the section is shown on figure 3.4. An uninterpreted section is provided in figure 3.16.
Figure 3.75: Major sequence 4 (MS 4) is highlighted in black on the three line drawings (LC 2, K 3, and B 2) of the Lower Congo Basin. MS 4 is thinnest in the Kwanza Basin. The vertical scale is in seconds TWT. The locations of the line drawings (LC 2, K 3, and B 2) are shown on figure 3.1.
In the three line drawings (LC 2, K 3, and B 2). The thickest deposits of MS 4 are found in
40 km. The vertical scale is in seconds TWT and the horizontal scale is in kilometers. The
information is shown on figure 3.1.
Congo Basin, slightly thinner deposits in the Benguela Basin, and significantly thinner in the Kwanza Basin.

Within each basin, the thickness of MS 4 also changes from east to west. The sequence consists of elastic sediments deposited between the Tortonian stage and the present. On the landward side of the basins, MS 4 has a similar thickness as MS 3, but relatively thicker than both MS 1 and MS 2 (Figures 3.76 and 3.77). A significant difference between MS 4 and MS 3 is that MS 4 begins farther basinward than MS 3. The MS 4 sediments prograding over MS 3 (Figure 3.78). Non-deposition and erosion occurs to the east, limiting the extent of MS 4. While MS 4 is thick were present under the shelf and slope, the sequence thins gradually westward through the basins (Figure 3.79). In the deeper parts of the basin, the sediments of MS 4 are affected by the salt structures. As the deposits of MS 2 and 3, the MS 4 deposits thins toward and over salt structures and thickens into the centers of minibasins (Figure 3.80).

The base of MS 4 is defined by an unconformity and its correlative conformity, SB 3. SB 3 is interpreted by both erosional truncation and onlap (Figures 3.71 and 3.72). The MS 3 reflectors terminate by erosional truncation underneath SB 3. This erosional truncation is identified in each basin and throughout the basin. The erosion occurred in shallow as well as deeper water settings. Above SB 3, reflectors of MS 4 onlap the sequence boundary. The onlap terminations are noted in each of the basins and throughout the basins. The amplitude associated with this boundary is not particularly strong (Figure
Figure 3.76: Major sequence 4 (MS 4), bounded above by the seafloor and below by sequence boundary 3, is thick in the shelf and slope regions. Sequence boundary 3 (SB 3) is a thick black line and labeled as ‘SB 3.’ Note that MS 4 varies between 1 and 2 seconds (TWT) thickness. The thickness of MS 4 is similar to that of MS 3, but both MS 1 and MS 2 are thinner than MS 4. This seismic section is from the Lower Congo Basin, profile LC 3. The location of the section is shown on figure 3.2. An uninterpreted section is provided in figure 3.6.
Figure 3.77: The thickness of major sequence 3 (MS 3), bounded above by sequence boundary 3 and below by sequence boundary 2, is similar to the thickness of major sequence 4 (MS 4), bounded above by the seafloor and below by sequence boundary 3. Sequence boundaries 2 and 3 (SB 2 and SB 3) are thick black lines and labeled as 'SB 2' and 'SB 3.' Note that MS 3 varies between 1 and 1.5 seconds (TWT) thickness compared with the thickness of 1 to 2 seconds of MS 4 in figure 3.76. This seismic section is from the Kwanza Basin, profile K 4. The location of the section is shown on figure 3.3. An uninterpreted section is provided in figure 3.11.
Figure 3.78: Major sequence 4 (MS 4), bounded above by the seafloor and below by sequence boundary 3, progrades over major sequence 3 (MS 3), bounded above by sequence boundary 3 and below by sequence boundary 2. Sequence boundaries 2 and 3 (SB 2 and SB 3) are thick black lines and labeled as ‘SB 2’ and ‘SB 3.’ Note that the reflectors of MS 4 prograde over MS 3 in the western (left) half of the section. This seismic section is from the Benguela Basin, profile B 4. The location of the section is shown on figure 3.4. An uninterpreted section is provided in figure 3.16.
Figure 3.79: Major sequence 4 (MS 4), bounded above by the seafloor and below by sequence boundary 3, thins basinward. Sequence boundary 3 (SB 3) is a thick black line and labeled as ‘SB 3.’ The thickness of MS 4 thins from 1.25 seconds to 2/3 seconds from east (right) to west (left). This seismic section is from the Lower Congo Basin, profile LC 3. The location of the section is shown on figure 3.2. An uninterpreted section is provided in figure 3.7.
Figure 3.80: The thickness of major sequence 4 (MS 4), bounded above by the seafloor and below by sequence boundary 3, varies over minibasins. Sequence boundary 3 (SB 3) is a thick black line and labeled as ‘SB 3.’ MS 4 thickens toward the center of minibasins and thins toward and over salt structures. This seismic section is from the Lower Congo Basin, profile LC 3. The location of the section is shown on figure 3.2. An uninterpreted section is provided in figure 3.9.
The difference in seismic velocity between MS 3 and 4 is not large. The average seismic velocity of MS 3 is 2300 meters/second, while the velocity of MS 4 is 2100 meters/second.

The seismic character of MS 4 is similar between the three basins. Along a given profile within a basin, the internal character of the sequence changes drastically. The sequence consists of concordant, divergent, convergent, faulted, and chaotic reflectors. 'Railroad track' or concordant reflectors are present under the slope in some areas as well as at the western extent of the basins (Figure 3.82). Due to the topography and dynamic system of salt structures and minibasins, reflectors diverge and converge about structures (Figure 3.83). Faults cut MS 4 with slight offset, mainly in the shelf region (Figure 3.84). Chaotic patches of reflectors occur within MS 4 (Figure 3.85). These chaotic areas are channel complexes. The spacing and thickness of reflectors is similar to MS 3, narrower and thinner than MS 1 and 2. The amplitude of reflectors in MS 4 varies vertically and laterally (Figure 3.86).

Within MS 4, at least two sequences can be interpreted in each of the three basins (Figures 3.87 and 3.88). In the Lower Congo Basin, which has the thickest MS 4 deposits, five sequences within MS 4 can be identified and correlated through most of the basin (Figure 3.89). The four sequence boundaries interpreted within the Lower Congo Basin may match four of these six medium sequence boundaries identified in Miocene to
Figure 3.81: Sequence boundary 3, bounding MS 3 and MS 4, is not recorded as a strong reflector. Sequence boundary 3 is noted by arrows. The seismic velocity contrast between the sediments of MS 3 and MS 4 is small, therefore the reflection does not have a large amplitude. This seismic section is from the Benguela Basin, profile B 4. The location of the section is shown on figure 3.4. An uninterpreted section is provided in figure 3.18.
Figure 3.82: Major sequence 4 (MS 4), bounded above by the seafloor and below by sequence boundary 3, contains concordant reflectors. Sequence boundary 3 (SB 3) is a thick black line and labeled as ‘SB 3.’ Note the relative concordance, ‘railroad track’ character, of the MS 4 reflectors across this section. This seismic section is from the Kwanza Basin, profile K 4. The location of the section is shown on figure 3.3. An uninterpreted section is provided in figure 3.13.
Figure 3.83: Major sequence 4 (MS 4), bounded above by the seafloor and below by sequence boundary 3, contains converging and diverging reflectors. Sequence boundary 3 (SB 3) is a thick black line and labeled as ‘SB 3.’ Note that the reflectors within MS 4 diverge into minibasins and converge over salt structures. This seismic section is from the Lower Congo Basin, profile LC 3. The location of the section is shown on figure 3.3. An uninterpreted section is provided in figure 3.9.
Figure 3.84: Major sequence 4 (MS 4), bounded above by the seafloor and below by sequence boundary 3, is slightly faulted in the shelf region. Sequence boundary 3 (SB 3) is a thick black line and labeled as 'SB 3.' Note that a couple of the faults that disturb the MS 3 reflectors (between SB 2 and SB 3) does move sediments of MS 4. This seismic section is from the Kwanza Basin, profile K 4. The location of the section is shown on figure 3.3. An uninterpreted section is provided in figure 3.11.
Figure 3.85: Major sequence 4 (MS 4), bounded above by the seafloor and below by sequence boundary 3, contains patches of chaotic reflectors. Sequence boundary 3 (SB 3) is a thick black line and labeled as 'SB 3.' Note the chaotic pattern of reflectors that occurs in patches within MS 4. These chaotic areas may be channel complexes. This seismic section is from the Benguela Basin, profile B 4. The location of the section is shown on figure 3.4. An uninterpreted section is provided in figure 3.17.
Figure 3.86: Reflectors within major sequence 4 (MS 4), bounded above by the seafloor and below by sequence boundary 3, vary in amplitude laterally and vertically. Sequence boundary 3 (SB 3) is a thick black line and labeled as 'SB 3.' Note the variable in the amplitude of the reflectors across the seismic section and within MS 4. This seismic section is from the Lower Congo Basin, profile LC 3. The location of the section is shown on figure 3.2. An uninterpreted section is provided in figure 3.8.
Figure 3.87: Major sequence 4 (MS 4), bounded above the seafloor and below by sequence boundary 3, is subdivided into two sequences in the Benguela Basin. Sequence boundary 3 is a thick black line and labeled as 'SB 3.' The sequence boundary separating the sequences within MS 4 is the black line between the seafloor and SB 3. The sequence boundary within MS 4 can be correlated within the Benguela Basin. However, the boundary can not be correlated northward from the Benguela Basin to the Kwanza or Lower Congo Basins. This seismic section is from the Benguela Basin, profile B 4. The location of the section is shown on figure 3.4. An uninterpreted section is provided in figure 3.17.
Figure 3.88: Major sequence 4 (MS 4), bounded above the seafloor and below by sequence boundary 3, is subdivided into two sequences in the Kwanza Basin. Sequence boundary 3 is a thick black line and labeled as ‘SB 3.’ The sequence boundary separating the sequences within MS 4 is the black line between the seafloor and SB 3. The sequence boundary within MS 4 can be correlated within the Kwanza Basin. However, the boundary cannot be correlated from the Kwanza Basin to the Benguela or Lower Congo Basins. This seismic section is from the Kwanza Basin, profile K 4. The location of the section is shown on figure 3.3. An uninterpreted section is provided in figure 3.12.
Figure 3.89: Major sequence 4 (MS 4), bounded above the seafloor and below by sequence boundary 3, is subdivided into five sequences in the Lower Congo Basin. Sequence boundary 3 is a thick black line and labeled as ‘SB 3.’ The sequence boundaries separating the sequences within MS 4 are the black lines between the seafloor and SB 3. The sequence boundaries within MS 4 can be correlated within the Lower Congo Basin. However, the boundary cannot be correlated from the Lower Congo Basin to the Benguela or Kwanza Basins. This seismic section is from the Lower Congo Basin, profile LC 3. The location of the section is shown on figure 3.2. An uninterpreted section is provided in figure 3.6.
Recent time, 0.8, 1.6, 2.4, 3.0, 3.8, or 5.5 Ma. The one sequence boundary found in all of the basins could be one of the same date candidates.

The top of MS 4 is defined by the seafloor. The surface does have erosional truncation of reflectors (Figure 3.90). Along the slope and deeper shelf, the reflectors of MS 4 terminate by erosional truncation underneath the seafloor. In the deeper portions of the three basins, reflectors experience erosional truncation adjacent to salt structures (Figure 3.91).

3.6 Lower Congo Basin seismic sequence stratigraphy

In addition to the four major sequences and three major sequence boundaries correlated through all of the Angolan basins, the Lower Congo Basin has local sequences and boundaries (Figure 3.21). Some of these sequences may be equivalent to sequences found in the other two basins, but they can not be correlated with the same degree of confidence as the four major sequences. Other sequences found in the Lower Congo Basin do not have any obvious equivalents in the other Angolan basins.

In the Lower Congo Basin, MS 1 is separated in two sequences. Although not directly correlatable, these two sequences appear to be similar to the two sequences within MS 1 of the Benguela Basin. In the Benguela Basin, the boundary between these two sequences is correlated with DSDP well data and dated as late Albian. According to Hardenbol et al. (1998), there are two medium sequence boundaries in the late Albian, 98
Figure 3.90: Reflectors of major sequence 4 (MS 4), bounded above by the seafloor and below by sequence boundary 3, are erosionally truncated at the seafloor. Sequence boundary 3 (SB 3) is a thick black line and labeled as ‘SB 3.’ Along the shelf and slope, MS 4 reflectors terminate by erosional truncation at the seafloor. This seismic section is from the Benguela Basin, profile B 4. The location of the section is shown on figure 3.4. An uninterpreted section is provided in figure 3.16.
Figure 3.91: Reflectors of major sequence 4 (MS 4), bounded above by the seafloor and below by sequence boundary 3, are erosionally truncated adjacent to salt structures. Sequence boundary 3 (SB 3) is a thick black line and labeled as ‘SB 3.’ Adjacent to salt structures, MS 4 reflectors terminate by erosional truncation at the seafloor. This seismic section is from the Kwanza Basin, profile K 4. The location of the section is shown on figure 3.3. An uninterpreted section is provided in figure 3.14.
and 99 Ma. The sequence boundary within MS 1 may be one of these medium sequence boundaries or an amalgamation of both. The sequence boundary within MS 1 is found on the two southern dip profiles of the Lower Congo Basin. This boundary is interpreted with confidence in the western and central portions of the basin.

MS 2 is separated into three sequences with two sequence boundaries in the Lower Congo Basin (Figure 3.55), as well as in the other two basins. These three sequences may be the equivalent to those interpreted in the southern basins, but their sequence boundaries can not be correlated with the same confidence as the major sequences. The sequence boundaries separating the sequences within MS 2 could not be directly correlated with age dates. Based on the time interval they occupy and the Hardenbol et al. (1998) chart, the two boundaries could be one of these sequence boundaries: 49.5, 58.5, 68, and 80 Ma. One of the boundaries is interpreted with confidence throughout the basin. The other boundary is only interpreted as an unconformable surface in the slope and shelf region of the southernmost dip profile.

Within the Lower Congo Basin, MS 3 can be separated into three sequences (Figure 3.69). These three sequences may be equivalents to the three sequences interpreted within MS 3 in the Kwanza Basin. They may also be equivalents to three of the five sequences within MS 3 in the Benguela Basin, or amalgamations of those five sequences. The two sequence boundaries within the MS 3 of the Lower Congo Basin may be the 21 and 30 Ma major sequence boundaries of Hardenbol et al. (1998). One of the two
sequence boundaries is correlated throughout the basin with confidence. The other sequence boundary is interpreted through most of the basin, only seemingly absent in the westernmost portion of the basin above the massive salt. The confidence in this boundary decreases in the western extremes of the basin because the sequences become relatively thin with few defining reflectors.

More sequences within MS 4 are identified in the Lower Congo Basin than in any other Angolan basin. MS 4 can be separated into five sequences in the Lower Congo Basin (Figure 3.89), while only into two sequences in the Kwanza and Benguela Basins. The four sequences boundaries can not be directly correlated with dated material from available wells, but they may be equivalent to four of the medium sequence boundaries identified in Hardenbol et al. (1998), 0.8, 1.6, 2.4, 3.0, 3.8, or 5.5 Ma. All four of the sequence boundaries are interpreted in the shelf and slope region of the Lower Congo Basin. To the north of the basin, three of the boundaries are correlated from east to west across the basin. One of the boundaries is restricted to the shallower setting. On the southernmost profile, only one of the boundaries is interpreted in the western portion of the basin. The increased number of sequences to the north may be due to the improved resolution acquired by the increased sediment output from the Congo River during MS 4.

For a more detailed study of the sequences and systems tracts of the Lower Congo Basin, the reflectors under the current shelf were examined (Figure 3.92). One dip profile was chosen for detailed interpretation (Figure 3.92a). The profile was chosen over the other
Figure 3.92: a) Seismic section used for the detailed sequence stratigraphic interpretation of the Lower Congo Basin. This seismic section is part of line LC 2. Major sequence boundaries, SB 2 and SB 3, are labeled. Lower order sequence boundaries (sb) are also labeled. Interpretation displayed in figure 3.92b. Chronostratigraphic chart in figure 3.92c.
Figure 3.92: b) Detailed sequence stratigraphic interpretation of the shelf area of line LC 2 of the Lower Congo Basin. The yellow lines are lowstand deposits. The green lines represent transgressive deposits. The orange lines are highstand deposits. The major sequence boundaries are labeled, SB 2 and SB 3. The other sequence boundaries interpreted within the Lower Congo Basin are labeled as ‘sb.’
Figure 3.92: c) Chronostratigraphic chart for the Lower Congo Basin based on the detailed sequence stratigraphic interpretation of line LC 2. Lowstand deposits are yellow lines. Transgressive deposits are green lines. Highstand deposits are orange lines. Forty two sequence boundaries are identified. The major sequence boundaries (SB 2 and SB 3) are labeled. The additional sequence stratigraphic boundaries (sb) are also labeled.
two dip sections because of the clarity and detail of its reflectors and the relative little structural influence. The shelf section of the Lower Congo dip profile was analyzed on a reflector by reflector basis. Fine scale sequences and systems tracts were interpreted on the section (Figure 3.92b). A chronostratigraphic chart was drawn from the seismic interpretation (Figure 3.92c). The chronostratigraphic chart shows the detail of sequence stratigraphy which when one looks only at the regional profiles and major sequences.

The detailed Lower Congo interpretation reveals more sequences than those of the Kwanza and Benguela Basins. In the area interpreted, 42 sequences and sequence boundaries were found. The reflector by reflector interpretation was initiated above the structurally altered Cretaceous strata. The oldest sequence boundary is the boundary that separates the two of the medium sequences within MS 2. This boundary may be correlated with dates between 50 and 80 Ma. The detailed interpretation spans from the Late Cretaceous/early Tertiary to Pliocene. The interpretation does not continue to the most recent sediments because structural movement obscures the patterns.

Between the Late Cretaceous/early Tertiary and middle Oligocene (boundaries 1 - 11), there are 10 sequences which can be identified in the Lower Congo Basin. These sequences have shelf breaks much farther east than the position of the present shelf break. Several of the sequences contain lowstand, transgressive, and highstand system tracts. Overall, these sequences are prograding steadily to the west.
Between the middle Oligocene and Late Miocene (boundaries 11 – 36), there are 25 sequences. Two of the sequence boundaries within this interval are the boundaries that separate MS 3 into three sequences. The lower sequence boundary, interpreted on the regional profiles, is boundary 20. The upper sequence boundary is boundary 23.

Between boundaries 11 and 20, the sequences continue to prograde steadily westward. Several of the sequences are complete with a lowstand, transgressive, and highstand system tracts. Some of the lower sequences display only lowstand and highstand system tracts. In the upper sequences in this interval, only the transgressive and highstand tracts are visible. The lowstand system tract may be present off the western edge of the interpreted area. Between boundaries 20 and 23, progradation continues. The lowstand and transgressive system tracts are shifted to the west and not always visible within the interpreted area. Between boundaries 23 and 36, progradation continues, with only transgressive and highstand deposits in the interpreted area. A significant transgression occurs around boundary 30.

At SB 3, boundary 36, the shelf break is pushed back to the east. Between the Late Miocene and Pliocene (boundaries 36 – 42), the sequences once again prograde. The dominant system tract visible in the interpreted area is the highstand system tract. The transgressive system tracts periodically are able to reach eastward over the highstand deposits. The lowstand system tracts can not be seen in the interpreted area, they are assumed to be present to the west. Additional boundaries would be interpreted in this
interval, if a larger region could be interpreted. Some sequence boundaries may be amalgamated with others in the interpreted area. The amalgamated boundaries may separate to the west. Unfortunately the reflectors are disrupted to the west by faults. Thus, due to these faults, stratigraphic patterns can not be clearly identified.

Within the Lower Congo Basin, several orders of sequences are identified. The four major sequences are correlated throughout the basin and with sequences in the other basins. These major sequences span time intervals of 10 to 50 My. The major sequences are considered to be second-order sequences. The 13 sequences that can be separated within these major sequences are considered to be third-order sequences. The 42 sequences which are found be detailed interpretation of reflectors are considered to be third to fourth-order sequences.

3.7 Kwanza Basin seismic sequence stratigraphy

The Kwanza Basin contains fewer sequences of lower order than the Lower Congo or Benguela Basins (Figure 3.22). The Kwanza Basin has four major sequences as the other two basins do. However, within the major sequences, only a few sequences can be separated. The lack of finer resolution of sequences compared to the other basins may be due to a lower sediment input.

MS 1 can be separated into two sequences in the Kwanza Basin (Figure 3.40). These two sequences may be equivalent to the two sequences within MS 1 in the Lower Congo and
Benguela Basins. However, the sequence boundary can not be correlated with a high
degree of certainty between the three basins. In the Benguela Basin, the boundary
separating these two sequences is correlated with DSDP well data and dated as late
Albian. According to Hardenbol et al. (1998), there are two medium sequence
boundaries in the late Albian, 98 and 99 Ma. The sequence boundary within MS 1 may
be one of these medium sequence boundaries or an amalgamation of both. This sequence
boundary within MS 1 is interpreted on all of the seismic lines in the Kwanza Basin. The
boundary is present throughout the basin in the shallow and deep sections. On a few of
the profiles, the boundary becomes unclear in the western edge of the basin.

As in the other two basins, MS 2 is separated into three sequences with two sequence
boundaries in the Kwanza Basin. These three sequences may be the equivalent to those
interpreted in the other basins, but their sequence boundaries can not be correlated with
the same confidence as the major sequences. The sequence boundaries separating the
sequences within MS 2 could not be directly correlated with age dates. Based on the time
interval they occupy and the Hardenbol et al. (1998) chart, the two boundaries could be
one of these sequence boundaries: 49.5, 58.5, 68, and 80 Ma. The upper of the two
boundaries is present on all the seismic lines, throughout the basin. The only exception is
the shelf region of the southernmost seismic line. The lower of the two boundaries is
only present in the eastern portion of the basin. The lower boundary is present under the
shelf and slope region and extends slightly into deeper water. The boundary is not
present as a unique surface in the western portion of the basin. It may be amalgamated
with another boundary. The lower boundary is also not present under the shelf region of the southernmost seismic line.

Within the Kwanza Basin, MS 3 can be separated into three sequences (Figure 3.70). These three sequences may be equivalents to the three sequences interpreted within MS 3 in the Lower Congo Basin. They may also be equivalents to three of the five sequences within MS 3 in the Benguela Basin, or amalgamations of those five sequences. The two sequence boundaries within the MS 3 of the Kwanza Basin may be the 21 and 30 Ma major sequence boundaries of Hardenbol et al. (1998). The upper boundary is present through most of the basin. This boundary is only absent on one of the profiles on the western edge, where the post-salt section thins significantly. The lower boundary is not as widespread. This boundary is interpreted under the shelf on the central three profiles, but not on the northern or southernmost profile. The lower boundary is present in the center of the basin on all of the seismic lines.

As in the Benguela Basin, MS 4 can be separated into two sequences in the Kwanza Basin (Figure 3.88). Only in the Lower Congo Basin is this major sequence separated into five sequences. The sequence boundary separating the two sequences can not be directly correlated with dated material, but may be equivalent to one of the medium sequence boundaries identified in Hardenbol et al. (1998), 0.8, 1.6, 2.4, 3.0, 3.8, or 5.5 Ma. This sequence boundary is present through most of the basin. On the present shelf,
the boundary often intersects the seafloor. At the western extent of the basin, where the sediment package thins, the boundary is not obvious on all of the profiles.

For a detailed study of the sequences and systems tracts of the Kwanza Basin, the reflectors under the current shelf and upper slope were examined (Figure 3.93). One dip profile was chosen for detailed interpretation (Figure 3.93a). The profile was chosen over the other two dip sections because of the clarity and detail of its reflectors and the relative little structural influence. The lower portion of the section does have a large structural influence, but the upper portion is less disturbed and clearer than any other Kwanza profile. The shelf/upper slope section of the profile was analyzed on a reflector by reflector basis. Fine scale sequences and systems tracts were interpreted on the section (Figure 3.93b). A chronostratigraphic chart was drawn from the seismic interpretation (Figure 3.93c). The chronostratigraphic chart shows the detail of sequence stratigraphy which when one looks only at the regional profiles and major sequences.

The detailed Kwanza interpretation has fewer sequences than those of the Lower Congo and Benguela Basins. In the area interpreted, 11 sequences and sequence boundaries were found. The reflector by reflector interpretation was initiated above the rafts and faults of the Cretaceous. The first sequence boundary is SB 2, which separates MS 2 and 3. This boundary may be correlated with a date of 30.0 Ma. The detailed interpretation spans from the early Tertiary to Pliocene. The interpretation does not continue to the
Figure 3.93a: Seismic section used for the detailed sequence stratigraphic interpretation of the Kwanza Basin. This seismic section is part of line K2. Major sequence boundaries, SB 1 and SB 3, are labelled. Lower order sequence boundaries (sb) are also labelled. Chronostratigraphic chart in figure 3.93b. Interpretation displayed in figure 3.93c.
Figure 3.93: b) Detailed sequence stratigraphic interpretation of the shelf area of line K 2 of the Kwanza Basin. The yellow lines are lowstand deposits. The green lines represent transgressive deposits. The orange lines are highstand deposits. The major sequence boundaries are labeled, SB 2 and SB 3. Other sequence boundaries interpreted within the Kwanza Basin are labeled as 'sb.'
Figure 3.93: c) Chronostratigraphic chart for the Kwanza Basin based on the detailed sequence stratigraphic interpretation of line K 2. Lowstand deposits are yellow lines. Transgressive deposits are green lines. Highstand deposits are orange lines. Eleven sequence boundaries are identified. The major sequence boundaries (SB 2 and SB 3) are labeled. The additional sequence stratigraphic boundaries (sb) are also labeled.
most recent sediments because the reflectors to the west of this section become difficult to distinguish and stratigraphic patterns become unclear.

The first sequence boundary (boundary 1) is SB 2. This boundary erosional truncation reflectors below. Above the boundary, a complete sequence with a lowstand, transgressive, and highstand system tracts is deposited. The overlying sequences, separated by boundaries 2 – 4, prograde toward the west. These sequences contain most of the system tracts, except for the sequence between boundary 4 and 5. This upper sequence contains concordant reflectors that to the east are incised and completely eroded. These reflectors are interpreted as highstand deposits topping off a prograding sequence.

Boundary 5 is the lower sequence boundary within MS 3. The boundary erodes into the underlying sequence in the eastern portion of the section. The eroded area is filled by prograding highstand deposits between boundaries 5 and 6. A transgressive system tract is deposited over boundary 6. Progradation returns in the upper portion of the sequence between boundaries 6 and 7.

Boundary 7 is SB 3, separating MS 3 and 4. The sequence boundary erodes into the previous sequence. A transgressive system tract is deposited directly over the boundary in this area. Above SB 3, within MS 4, several sequences are identified. The sequences are separated by boundaries 8 – 11. The sequences are overall prograding, but contain
transgressive and highstand system tracts. The lowstand system tracts of these sequences would be found farther west.

Within the Kwanza Basin, several orders of sequences are identified. The four major sequences are correlated throughout the basin and with sequences in the other basins. These major sequences span time intervals of 10 to 50 My. The major sequences are considered to be second-order sequences. The 10 sequences that can be separated within these major sequences are considered to be third-order sequences. The 11 sequences that are found by detailed interpretation of reflectors are considered to be third-order sequences.

3.8 Benguela Basin seismic sequence stratigraphy

The Benguela Basin has sequences in addition to the four major sequences interpreted in all of the basins (Figure 3.23). The Benguela Basin has similar sequences within MS 1, 2, and 4, compared with the other two basins. However, in MS 3 there are five sequences in Benguela, while only three in the Lower Congo and Kwanza Basins.

In the Benguela Basin, as in the other basins, MS 1 is separated in two sequences. The sequence boundary separating the two sequences is correlated to an unconformable surface in the DSDP wells. The age of the surface is late Albian. According to Hardenbol et al. (1998), there are two medium sequence boundaries in the late Albian, 98 and 99 Ma. This boundary is assumed to be 98 or 99 Ma. The sequence boundary is
found on all seismic lines. The only area where it is difficult to interpret the surface is on the southernmost profile under the present shelf.

MS 2 is separated into three sequences with two sequence boundaries in all three basins (Figure 3.56). The three sequences may have the same timing in all three basins, but their sequence boundaries can not be correlated with the same confidence as the major sequences. Since they fall between 39.5 and 90 Ma, the sequence boundaries may be one of these boundaries on the Hardenbol et al. (1998) chart, 49.5, 58.5, 68, and 80 Ma. The lower of the two sequence boundaries is located throughout the basin. It is missing on the western side of one of the central seismic lines. The upper sequence boundary is present on all of the Benguela seismic lines. It is missing on the same western side of one of the lines, as the upper boundary. The sequence boundary is also absent under the present shelf and slope area in the basin.

Within the Benguela Basin, MS 3 can be separated into five sequences (Figure 3.68). Both the Lower Congo and Kwanza Basin have only three sequences within MS 3. These two basins are either lacking the resolution to define the extra sequences or never experienced the events that created the sequences in the Benguela Basin. The four sequence boundaries in MS 3 are not directly dated. Since they fall between ages of 10.5 and 39.5 Ma, two probable candidates are 21 and 30 Ma. Both of these ages correspond to major sequence boundaries according to Hardenbol et al. (1998). Candidates for the other two sequence boundaries are medium sequence boundaries in this time interval,
15.5, 16.5, 25.5, and 36 Ma. All of the four sequence boundaries are interpreted in the shelf, slope, and central regions of the basin. In the western edge of the basin, only one of the boundaries is evident in the northern two seismic lines.

As in the Kwanza Basin, MS 4 is separated into two sequences in the Benguela Basin (Figure 3.87). In the Lower Congo Basin, five sequences are identified in this same interval. The sequence boundary separating the two sequences can not be directly correlated with dated material, but may be equivalent to one of the medium sequence boundaries identified in Hardenbol et al. (1998), 0.8, 1.6, 2.4, 3.0, 3.8, or 5.5 Ma. This sequence boundary is present throughout the basin. The surface intersects the seafloor along the present shelf and near salt structures.

For a detailed study of the sequences and systems tracts of the Benguela Basin, the reflectors under the current shelf and upper slope were examined (Figure 3.94). One dip profile was chosen for detailed interpretation (Figure 3.94a). The profile was chosen over the other two dip sections because of the clarity and detail of its reflectors and the relative little structural influence. The shelf/upper slope section of the profile was analyzed on a reflector by reflector basis. Fine scale sequences and systems tracts were interpreted on the section (Figure 3.94b). A chronostratigraphic chart was drawn from the seismic interpretation (Figure 3.94c). The chronostratigraphic chart shows the detail of sequence stratigraphy which when one looks only at the regional profiles and major sequences.
Figure 3.94: a) Seismic section used for the detailed sequence stratigraphic interpretation of the Benguela Basin. This seismic section is part of line B 2. Major sequence boundaries, SB 1, SB 2, and SB 3, are labeled. Lower order sequence boundaries (sb) are also labeled. Interpretation displayed in figure 3.94b. Chronostratigraphic chart in figure 3.94c.
Figure 3.94: b) Detailed sequence stratigraphic interpretation of the shelf area of line B 2 of the Benguela Basin. The yellow lines are lowstand deposits. The green lines represent transgressive deposits. The orange lines are highstand deposits. The major sequence boundaries are labeled, SB 1, SB 2, and SB 3.
Figure 3.94: c) Chronostratigraphic chart for the Bengeula Basin based on the detailed sequence stratigraphic interpretation of B 2. Lowstand deposits are yellow lines. Transgressive deposits are green lines. Highstand deposits are orange lines. Twenty seven sequence boundaries are identified. The major sequence boundaries (SB 1, SB 2, SB 3) are labeled. The additional sequence stratigraphic boundaries (sb) are also labeled.
The detailed Benguela interpretation has fewer sequences than the one of the Lower Congo, but more than the one of the Kwanza Basin. In the area interpreted, 27 sequences and sequence boundaries were found. The reflector by reflector interpretation was initiated above the remaining Aptian salt. The first sequence boundary is in the upper of the two sequences within MS 1. This boundary is therefore between the age of 90 and 98 Ma. The detailed interpretation spans from the Late Cretaceous to Pliocene. The interpretation does not continue to the most recent sediments because the reflectors to the west of this section become difficult to distinguish and stratigraphic patterns become unclear. The detailed interpretation of the Benguela Basin spans a longer time interval than the detail interpretations of the other two basins.

Between the Late Cretaceous and Turonian (boundaries 1 - 3), 3 sequences are identified. These sequences are not all complete with a lowstand, transgressive, and highstand system tract. However, the sequences show erosive events and overall backstepping toward the east. Boundary 3 is SB 1.

Between boundaries 3 and 6 is MS 2. Only three sequences are identified in this Turonian to Rupelian major sequence. The two boundaries, 4 and 5, would correspond to the sequence boundaries which separated three sequences within MS 2. The earlier two sequences are overall transgressive. The third sequence is aggradational. Boundary 6 is SB 2.
Between the middle Oligocene and Late Miocene (boundaries 6 – 26), there are 20 sequences identified in the Benguela Basin. Four of the boundaries are correlated with the sequence boundaries that separate MS 3 into five sequences in the Benguela Basin. The earliest of these four boundaries is boundary 8. The next one is boundary 16. The third one is boundary 17. The final one is boundary 23. Between boundaries 6 and 8, the two sequences continue to be aggradational. Changes occur between boundaries 8 and 16. At first, a transgression occurred (9 - 11), then progradational strata were deposited (14 - 16). Between boundaries 16 and 17, a slight backstepping occurred. Progradation continued between boundaries 17 and 23. Between boundaries 23 and 26, the sequences are represented by dominantly prograding highstand deposits in this area.

Above boundary 26, which is SB 3, 2 more prograding sequences occur. Both of these sequences contain a transgressive and highstand system tract. The lowstand system tract of both sequences may be found to the west. These two sequences display an overall prograding pattern that was deposited after the formation of boundary 14.

Within the Benguela Basin, several orders of sequences are identified. The four major sequences are correlated throughout the basin and with sequences in the other basins. These major sequences span time intervals of 10 to 50 My. The major sequences are considered to be second-order sequences. The 13 sequences that can be separated within these major sequences are considered to be third-order sequences. The 27 sequences
which are found by the detailed sequence stratigraphic interpretation are considered to be third to fourth-order sequences.
CHAPTER 4 - UNDERSTANDING UNCONFORMITIES

4.1 Introduction

To understand the development of the Angolan margin, the geologic record is separated into depositional sequences bounded by unconformities and their correlative conformities. To appreciate the changes between the sequences, the mechanism of formation of the sequence boundary must be understood. The three mechanisms that can create an unconformity are sea-level fluctuations, tectonic activity, and changes in current circulation patterns. Each of these mechanisms will create unconformities with different characteristics. The mechanisms can also combine to enhance or detract from each other.

In this chapter, each of the three unconformity forming mechanisms, sea-level fluctuations, tectonics, and currents, are examined. The interaction of these mechanisms is explained. Then the formation of the Angolan margin unconformities is discussed. Several seismic sections are displayed in figures in this chapter. Figure 4.1 is a map of the seismic lines. The locations of the seismic sections are noted on the line drawings of figure 4.2.

4.2 Sea-level changes

4.2.1 Relative Sea-Level vs. Eustasy

The term eustasy introduced by Suess in 1888 refers to the change of worldwide sea-level. Relative sea-level factors eustasy with local conditions to determine whether sea-
Figure 4.1: The location of the seismic reflection data grid used in this study is displayed as heavy black lines. The seismic lines are labeled as Lower Congo Basin lines (LC 1, LC 2, and LC 3), Kwanza Basin lines (K 1, K 2, K 3, K 4, and K 5), Benguela Basin lines (B 1, B 2, B 3, and B 4), and strike lines (S 1, S 2, S 3, and S 4). The location of the DSDP site 364 is noted by a red dot. The map is the bathymetry/topography of the Angolan segment of the South Atlantic region based on satellite data, adapted from Sandwell and Smith (1997) (Marton et al, 2000).
Figure 4.2: Locations of seismic sections displayed in figures in this chapter. The seismic section boxes correspond to figure numbers used in this chapter. The locations of the line drawings (LC 2, K 2, K 3, B 3) are indicated.
In this chapter. The seismic sections are outlined by black boxes. The numbers above the locations of the line drawings (LC 2, K 2, K 3, and B 3) are shown on figure 4.1.
level is rising or falling compared to the floor of the basin. Sea-level may rise when glaciers are melting, but relative sea-level of a given basin may be decreasing if the tectonic subsidence is greater than sea-level rise. Relative sea-level is calculated by adding the effects of eustasy and tectonic subsidence or uplift.

Both eustasy and tectonic subsidence can have positive or negative changes. A rise in worldwide sea-level is considered to be a positive change, while a fall is considered a negative change regarding eustasy. A lowering or subsidence of the basin floor is a positive change, while a rise or uplift is a negative change in respect to tectonic subsidence. The combination of a positive change of eustasy and a negative change of tectonic subsidence (rising worldwide sea-level and rising basin floor) produces a larger rise of relative sea-level. Similarly, a negative change of eustasy combined with a positive change of tectonic subsidence (lowering worldwide sea-level and lowering basin floor) produce a larger fall of relative sea-level. The combination of both positive or both negative values leads to a smaller relative change, the direction of which depends on whether the eustatic or tectonic subsidence value is larger.

4.2.2 How sea-level changes create erosion and non-deposition

Sea-level changes are the primary control on erosion and non-deposition along margins. During times of low sea-level, the shelf and part of the slope are subaerially exposed. Rivers in the continent downcut because their base level, sea-level, has lowered. The
rivers erode the exposed land, bypass the exposed shelf and slope, and deposit the eroded sediments as part of the lowstand systems tract.

The lowstand system tract is composed of the basin floor fan, slope fan, and prograding wedge. The base of the lowstand system tract is an unconformity and its correlative conformity. The unconformable surface forms on the shelf and exposed portion of the slope. The correlative conformity is between the lowstand deposits in the basin and on the lower slope and the condensed deposits of the previous highstand.

As the sea-level rises, the shelf becomes flooded. The transgressive surface represents the first major flooding event to pass the shelf break and flood part of the shelf. During the transgressive systems tract, non-deposition occurs in regions not yet flooded. Condensed sections form in deep water areas. The majority of sediments are deposited on the shelf and upper slope overlying the unconformity created by erosion and non-deposition during the previous lowstand. The maximum flooding surface marks the end of the transgressive system tract and the beginning of the highstand system tract. The maximum flooding surface is not an unconformity.

During the highstand system tract, sediments may prograde over the shelf into the basin. A condensed section forms in the deep portions of the basin. The top of the highstand system tract is an unconformity in the shallow sections, the shelf and slope, and a correlative conformity in the deep section, lower slope and basin floor. The
unconformity forms when the top of the highstand deposits are exposed by another drop in relative sea-level. The exposed highstand deposits on the shelf and slope are eroded, creating the unconformity surface. In the basin, deposition is more continuous.

4.2.3 History of sea-level

Sea-level had fluctuated throughout the development of the Angolan margin. Sea-level is controlled by the volume of water in the oceans and the depth and area of the ocean basin. The concepts of sea-level changing with the volume of water present and the volume of the ocean basin can be visualized by a bucket of water.

Sea-level is similar to the level of water in a bucket. As we increase the volume of water in the bucket by pouring more in, the water level goes up. If we drain water from the bucket, the water level goes down. Adding or draining water to the bucket is similar to water leaving the oceans as ice in glaciers or glaciers melting and adding water to the oceans. If the sides of the bucket are moldable we can change the shape of the bucket. With the same volume of water a larger bucket would have a lower water level than a smaller bucket. A bulge in the base of the bucket would cause the water level to rise. As continents rift, oceans form, and subduction occurs, the shape of the oceans and thereby the space available for water changes. Changes in the rate of spreading at a mid-oceanic ridge can create a larger bulge at the ridge or change the profile of the crust moving away from the ridge. Each of these factors changes the shape of the oceanic basins and thereby sea-level.
Eustasy is recorded in the geologic record. Charts of eustatic curves of the Mesozoic and Cenozoic have been published and are widely accepted (Abreu et al., 1998) (Figure 4.3). Glacial eustasy, the worldwide change in sea-level due to glaciers, can be traced back to the base of the Lutetian stage, Middle Eocene (Abreu and Anderson, 1998). Evidence for eustasy exists much farther back in time than the Eocene. If glacial activity did not influence eustasy before the Eocene, perhaps another mechanism existed which controlled the amount of water available to fill the ocean basins.

If eustasy was not influenced by the volume of water available prior to the Eocene, then the changes in sea-level recorded in the geologic record are perhaps due to changes in the shape of the ocean basins. As the supercontinent of Pangea separated into the present continents, the ocean basins change dramatically. The oceans that had surrounded Pangea were subducted. New oceans formed between the newly rifted continents. The volume of the ocean basins varies greatly by the process of destroying oceanic crust at subduction zones and creating oceanic crust at mid-oceanic ridges. Due to thermal subsidence older oceanic crust is denser and provides a deeper basin. Freshly formed oceanic crust is less dense and closer to the sea-level. The profile of an ocean goes from the high mid-oceanic ridge to the low abyssal plain as the age of the oceanic crust increases and it thermally subsides. When the rate of oceanic spreading changes, the volume of the ocean basin is affected dramatically. An increase in the rate of spreading would produce more young, light crust. The increase of young crust relative to older
Figure 4.2: Long and short term eustatic curves (Haq et al., 1987) compared with the long term isotope curves (Abreu, 1998) and short term sequence stratigraphic (Hardenbol et al., 1998) and isotopic (Abreu and Haddad, 1998 and Abreu and Anderson, 1998) cycles (modified from Abreu, 1998).
crust decreases the volume of the ocean basin. While a decrease in the spreading rate, results in more older, subsided crust, and therefore increases the volume of the ocean basin.

4.2.4 How unconformities formed by sea-level changes are identified

During sea-level fluctuations, an unconformity forms during the fall and subsequent rise of relative sea-level. During the fall in sea-level, the shelf and the upper portion of the slope are exposed. Erosion occurs along the exposed region. Non-deposition also occurs in these exposed areas and the shallow marine areas as sediment bypasses toward the toe of the slope.

Erosional truncation and onlap defines the unconformity and correlative conformity on seismic profiles. Below the surface of an unconformity there may be erosional truncation on the shelf and upper slope regions. In the deeper regions, the surface will be concordant with underlying condensed section deposits of the previous highstand. Above the surface, reflectors of the lowstand and transgressive deposits will onlap the slope and shelf area. At the toe of slope and beyond, the overlying deposits of the lowstand will be concordant with the surface (Figure 4.4).

The extent of the unconformity will determine whether sea-level fluctuations created it. An unconformity formed by a fall and rise of sea-level will be regional. The unconformity and its correlative conformity will be present through individual basins,
Figure 4.4: a) Uninterpreted seismic section from the Lower Congo basin, line LC 2. The location of the section is shown in figure 4.2.
Figure 4.4: b) Seismic section from the Lower Congo basin, line LC 2. The location of the section is shown in figure 4.2. An unconformity is highlighted by a black line. Below the unconformity, reflectors terminate by erosional truncation and toplap. Above the unconformity, reflectors onlap and downlap onto the unconformity surface. A detailed sequence stratigraphic interpretation of this profile is displayed in figure 3.92.
from the shelf to the abyssal plain. The unconformity must also be traced between basins along a margin. The expression of the unconformity may vary since local factors differ between basins, but the surface must be regionally correlative.

4.3 Tectonics

4.3.1 The relation of erosion and non-deposition to tectonics

Tectonic events alone do not erode sediments. Unconformities associated with tectonic events were created with the assistance of wind and rivers, if subaerially exposed, or marine currents, if submarine. Without these erosional forces, tectonics can not produce an unconformity. Tectonics does influence erosion and non-deposition by changing topography. Through uplift, faulting, and folding, the surface (continental or seafloor) is altered. Deposition will occur in low areas and areas of high subsidence by faults. While high regions will be bypassed, experiencing non-deposition. The highs will be subjected to erosion by subaereal or submarine processes. Therefore even though the tectonic events do not erode, tectonics directly influences where deposition and erosion occurs, affecting the formation of an unconformity. Unconformities related to tectonic events are used as sequence boundaries.

4.3.2 Types of unconformities associated with tectonic events

The tectonic history of the Angolan margin can be separated into two tiers of tectonics. One tier is of the super-regional to regional scale, and the other tier is of a regional to local scale. The super-regional tier is created by tectonic events such as the breakup of
Pangea and the formation of the Atlantic Ocean between South America and Africa. The regional to local scale is created by local tectonic events that occurred offshore Angola.

The tectonic unconformities discussed in this section are part of the geologic record offshore Angola. The super-regional to regional scale unconformities include the rifting unconformities and the breakup unconformity. The regional to local scale unconformities include salt related and fault related surfaces.

Super-regional to regional scale unconformities occur with the breakup of the Pangean supercontinent begins in the Jurassic. Along the Angolan margin, the rifting begins in the Early Cretaceous (Nurnberg and Muller, 1991). Unconformities form during the rifting, because the rifting occurs in three distinct stages (Karner et al., 1997). Along Angola, the first rifting phase is in the early Berriasian. An unconformity separates deposits of the first rifting phase from deposits associated with the second, Hauterivian rifting. The third and final rifting occurs in the late Barremian (Karner et al., 1997). These rifting unconformities are created by subaerial erosion. The formation of the unconformity is due to rifting, sea-level and oceanic currents do not play a role.

Another type of tectonic unconformity recognized on passive margins is the breakup or onset of drift unconformity. This unconformity marks a great change in the conditions of the margins surrounding the forming sea. As the rifting stage ends, the deposition of sediments changes. During rifting, sediments are eroded off of horsts and deposited in
grabens. As the movement along the rift faults decreases, the patterns of erosion and deposition change significantly. The tectonic change between rifting and drifting creates an unconformity because of the changes in erosion and deposition (Figure 4.5).

Overlying the break up unconformity is a sag basin. Offshore Angola, the Cuvo/Chela sands separate the underlying rift section from the overlying salt. Along other Atlantic margins, the sag basin phase is much more pronounced.

Not all regional tectonic events are associated with unconformities. During the Cenomanian and Turonian, the thermal subsidence decreased (Walgenwitz et al., 1992). Subsidence also slowed after the Paleocene (Poag and de Graciansky, 1992). These changes in the rate of subsidence probably did not create unconformities.

The regional to local unconformities include unconformities related to salt tectonics. The Angolan margin contains many salt tectonic unconformities within its basins and minibasins. A salt basin formed as a result of the breakup of Pangea and drifting as the Atlantic Ocean formed. The Aptian Loeme evaporites were deposited over the syn-rift filled grabens and the post-rift Cuvo/Chela sands. The Aptian salt was deposited early in the drifting stage, while the South American and African continents were close and the sea was shallow and restricted. The salt basin extended from the Walvis Ridge to the Niger delta. During the Albian, thermal subsidence was rapid. The rapid subsidence provides accommodation space for over one kilometer of evaporites. The initial
Figure 4.5: a) Uninterpreted seismic section from the Kwanza basin, line K 2. The location of the section is shown in figure 4.2.
Figure 4.5: b) Seismic section from the Kwanza basin, line K 2. The location of the section is shown in figure 4.2. Faults and unconformities are highlighted by black lines. The thick black line is the breakup unconformity. Under this unconformity, reflectors terminate by erosional truncation and toplap. Above the unconformity, reflectors are disturbed from their original patterns by salt tectonics. Pre-rafts slid on the Aptian salt above the breakup unconformity. The post-salt unconformities are formed by relative sea level changes with interplay of sedimentation and salt movement. A detailed sequence stratigraphic interpretation of this profile is displayed in figure 3.93.
thickness of the salt was over one kilometer along the southern Angolan margin, but thinner to the north of Angola. Since the Late Cretaceous, the Aptian salt layer has deformed. During the drift stage, sediments were deposited over the salt layer initiating the movement of the salt. As salt flows within a basin due to the pressure of overburden, unconformities are formed (Figure 4.6). Salt withdraws from some areas and accumulates in adjacent areas. Mini-basins form in areas where the salt has withdrawn and are flanked by salt structures. As salt deforms a variety of salt structures can form. Offshore Angola, the salt has formed salt diapirs, walls, domes, tongues, and canopies.

Unconformities form within these mini-basins when the rates of salt flow and sediment accumulation vary. The growth of a salt structure maintains a surface high above the structure, and minibasins develop between salt structures due to salt withdrawal. Erosion and non-deposition will occur above salt structures, while sediments pond into the minibasins. As the salt structures deform and salt layers deflate, adjacent sediment layers may be rotated. The rotation of layers can lead to erosion and non-deposition in some areas of a minibasin, providing another mechanism for forming an unconformity. The salt tectonic unconformities have a wide range of aerial extent. While these unconformities could be regional in extent, most are restricted to a mini-basin and a few are basin-wide.

Another type of local tectonic event is faulting. The Angolan margin has experienced both extensional and contractional forces. The faulting, either normal or thrust, can
Figure 4.6: a) Uninterpreted seismic section from the Benguela basin, line B 3. The location of the section is shown in figure 4.2.
Figure 4.6: b) Seismic section from the Benguela Basin, B 3. The location of the section is shown in figure 4.2. Unconformities are highlighted by black lines. The thick black line highlights one of the unconformities. Under this unconformity, reflectors terminate by erosional truncation. Above the unconformity, reflectors terminate by onlap. Arrows highlight some of the terminations. The development of salt structures influences depositional patterns. The movement and rotation of strata enhances the unconformities.
create unconformities in the sediments adjacent to the faulting. These unconformities are locally restricted to a fault block, but may be correlated with unconformities in another fault block. Typically a fault unconformity will be contained in a mini-basin and within a basin.

If a fault cuts to the surface, or near the surface, it affects deposition and erosion. Sedimentation will increase on the low side of the fault and erosion will occur preferentially on the high side. As faults rotate layers, layers may become exposed and eroded. By changing the topography of the surface and rotating layers, faulting creates both erosion and non-deposition.

The Angolan margin also experienced episodes of tilting. In the Middle Eocene and again in the Oligocene, the Angolan margin was tilted westward (Walgenwitz et al., 1992). The tilting both exposed deposits to erosion and caused movement of the salt layer. Tilting of a margin creates extensive unconformities that could be regional to super-regional.

4.3.3 How are unconformities formed by tectonics identified

Unconformities created by tectonics can be regional or local in extent. Both regional and local tectonic unconformities are identified by erosional truncation of tilted strata, as well as possible onlap.
As layers are rotated or the surface is altered by tectonic events, erosion occurs. Depending on the scale of the event, the erosion may be confined to a single minibasin. Some erosion may be basin-wide. Large tectonic events, such as the breakup of Pangea, can create erosion along a continental margin. As deposition occurs around and after tectonic activity, layers will onlap surfaces that have been tilted by the tectonic events.

The combination of the erosion and deposition define the tectonic unconformities. Below the unconformity are erosional truncations. Above the unconformity, deposits onlap the surface. These erosional truncations and onlaps can occur across the margin and throughout the basin at any water depth. The lateral extent may be restricted within a minibasin or spread across the margin.

4.4 Currents

4.4.1 History of current patterns

As the Atlantic Ocean evolved, circulation patterns within it changed. Initially, circulation was restricted (Burke, 1975). Physical barriers isolated bodies of water. The restriction allowed the deposition of evaporites, the Aptian salt layer. As the ocean grew, the physical barriers were breached and climate evolved, creating circulation patterns that changed over geological time (Figure 4.7) (Berger and Wefer, 1996).

Current circulation in the Atlantic Ocean is composed of several bodies of water which develop in various areas of the ocean and travel around the ocean at specific depths
Figure 4.7: Evolution of deep and intermediate water circulation in the Atlantic Ocean during the Cenozoic. The cross sections show that the present circulation pattern between the North and South Atlantic developed as the characteristics of the water masses changed. The major South Atlantic circulation changes occurred before the Oligocene (Abreu, 1998).
(Schmitz, 1995 and Berger and Wefer, 1996). The North Atlantic Deep Water (NADW) forms in the North Atlantic Ocean. The NADW flows south at deep to intermediate water depths. Beneath the NADW in the South Atlantic Ocean is the Antarctic Bottom Water (AABW). The AABW is colder than the NADW and flows northward along the bottom of the ocean. Along the south edge of the Atlantic Ocean, the Antarctic Circumpolar Current (ACC) flows around Antarctica (Schmitz, 1995). In the South Atlantic, trade winds and westerlies control the upper water circulation (Figure 4.8) (Berger and Wefer, 1996). Currents form an anticlockwise flowing central gyre. The northern portion of the gyre is the western flowing South Equatorial Current. Then the Brazilian Current flows south along South America. The South Atlantic Current flows eastward at the base of the gyre. Along the African margin, the Benguela Current flows to the north (Stramma and Peterson, 1989; Berger and Wefer, 1996; and Garzoli and Gordon 1996).

The present circulation patterns and water bodies evolved through a series of changes in climate and geographic boundary conditions (Berger and Wefer, 1996). In the Aptian, the South Atlantic Ocean was still beginning to form. Restricted access by physical barriers provided an environment for evaporite deposition (Burke, 1975). Along the Angolan margin, a restricted basin filled with evaporites (Belmonte et al., 1965; Pautot et al., 1973; Burke, 1975; Evans, 1978; and de Ruiter, 1979). The basin was deeper to the south, in the Benguela Basin, and shallowed to the north, the Lower Congo Basin. During the Late Cretaceous, the deep waters of the ocean were poorly circulated.
Figure 4.8: Surface currents of the central and South Atlantic Ocean. The surface currents of the South Atlantic form an anticlockwise flowing gyre. The northern portion of the gyre is the western, northwestern flowing South Equatorial Current. Then the Brazil Current flows south along South America. The South Atlantic Current flows eastward at the base of the gyre. Along the African margin, the Benguela Current flows to the north. These surface currents affect the deposition and erosion of sediments along the west African and east Brazilian margins (Berger and Wefer, 1996).
Organic rich deposits resulted from the lack of circulation (Uchupi, 1992). Circulation developed aggressively in the Cenozoic. In the Middle Eocene to Late Oligocene, thermohaline circulation is initiated (Uchupi, 1992). Abyssal circulation begins in the Early Oligocene (Uchupi, 1992). During the Late Eocene, about 40 Ma, a significant change in circulation was caused by the northward movement of continents away from Antarctica (Figure 4.9) (Berger and Wefer, 1996). At this time, the ocean transitioned from a warm to cold ocean and the carbon compensation depth (CCD) dropped globally. During the Middle Miocene, at about 14 Ma, a similar cooling occurred (Berger and Wefer, 1996). At this time, the CCD dropped, a major ice cap began to form in Antarctica, the pre-AABW formed, and sea-level dropped (Uchupi, 1992). During the Late Miocene to Early Pliocene the AABW and a thick Antarctic ice sheet developed (Uchupi, 1992). The NADW formed at about 10 Ma in the Late Miocene (Berger and Wefer, 1996). With the AABW and NADW, the South Atlantic became a thoroughfare, transporting warm water to the North Atlantic and circulating the cold water out of the North Atlantic (Schmitz, 1995). Another cooling event occurred at about 3 Ma, Late Pliocene (Berger and Wefer, 1996). During the Neogene, the intensity of the bottom currents decreased within the Angolan basins (Uchupi, 1992).

Changes in the Cenozoic circulation patterns were due primarily to two causes. One cause is a change of the connections between the world’s oceans. When the connection between two oceans opens or closes, circulation in both oceans is affected. One example for the South Atlantic was the effect of the continents moving away from Antarctica in
Figure 4.9: Geography of the middle Eocene (ca. 45 Ma) and major valve points for ocean circulation. Tropical valves are closing (black bars), high latitude valves are opening (white bars) throughout the Tertiary. At this time, the northward movement of the continents away from Antarctica significantly alters ocean circulation (Berger and Wefer, 1996).
the Late Eocene (Beger and Wefer, 1996). Another cause of circulation changes is the raising or lowering of sea-level. The sea-level determines the amount and depth of submerged area. Simply dropping the sea-level below the shelf break of a continent could drastically change circulation pattern throughout the ocean. Recent glacial and interglacial cycles caused changes in Atlantic circulation (Berger and Wefer, 1996).

When changes in circulation occur, the oceans can respond in a number of ways. The composition of the water bodies may change. The path and depth of a water body’s flow may be drastically altered. The number of different water bodies may increase or decrease. As these water bodies shift and circulation patterns change, the continental margins can be significantly affected. Currents due to ocean circulation can erode sediments and redistribute those sediments along a continental margin.

4.4.2 How currents cause erosion and non-deposition

Currents create unconformities by erosion and inhibiting sedimentation. Oceanic currents are capable of eroding large amounts of sediments (Vianna and Faugères, 1998 and Cunningham et al., 1998). As a water body moves along a continental margin, it has the capability of forming an unconformity along the entire margin. Currents can cause non-deposition by either inhibiting sedimentation or not bringing sediment into the area. If an area only receives sediments from a given current and that current’s path is altered, then non-deposition would occur. Currents can also influence sedimentation in areas
protected from strong bottom currents. Deep, sheltered areas can accumulate sediment while surrounding exposed areas experience erosion by bottom currents.

The Brazilian margin has documented the effect of the Brazilian current. As sea-level and circulation patterns change, the Brazilian current migrates. The current erodes the bottom sediments as it passes over. Seismic sections display the effect of the current's erosive power. The focus of the erosion shifts east and west as the current's path alters (Figure 4.10) (Viana and Faugeres, 1998). Another example of bottom current erosion is in the North Scotia Ridge region. The ACC has vigorous bottom currents that not only inhibit sedimentation, but erode sediments. Figure 4.11 shows a channel created by erosive bottom currents of the AAC in the North Scotia Ridge region. The eroded channel is about 150 meters deep and 2 kilometers wide (Cunningham et al., 1998).

The Benguela Current has created erosion and caused non-deposition along the African margin. As it moves northward along the margin, the Benguela current erodes sediments under its flow (Figure 4.12). The currents along West Africa also carry eroded sediments to other areas. The currents determine where erosion and where deposition occurs. The Benguela Current formed during the Miocene. The current has not followed the same path throughout its history. Most notably, the location of the current's bend from a northern path to a northwestern path has shifted over time. In the past the bend occurred at approximately 17°S. Presently the bend is located farther south between 20°S and
Figure 4.10: The evolution of late Quaternary evolution offshore Brazil in three episodes (a, b, and c) corresponding to different sea level stands and positions of the Brazil Current. Numbers indicate the hypothetical current speeds in cm/s. X indicates flow into the page and a dot indicates flow direction towards the reader. Arrows indicate the direction of bed load transport. A longshore current, installed at the shelf edge - upper slope passage, is suggested during the Last Glacial Maximum (Vianna and Faugeres, 1998).
Figure 4.11: a) Single channel seismic reflection profile showing an eroded depression on the Falkland Plateau sea floor. The profile has vertical exaggeration in water of 4:1. b) Coincident 3.5 kHz sub-bottom profile. The profile has vertical exaggeration in water of 10:1. The depression is over 1 km wide and between 150 and 250 meters deep. The section is located about 100 km offshore with a water depth of approximately 1 km (Cunningham et al., 1998).
Figure 4.12: Seismic display from the Kwanza basin, K 3. The location of the section is shown in figure 4.2. The surface of the sea floor is highlighted by a black line. There are several depressions on this section. The largest one is over 2 km wide and 150 meters deep. The water depth is approximately 1500 meters. The channels on the sea floor can be formed by currents originating from updip on the margin or by oceanic currents flowing along the margin.
23°S. As the bend migrated, the areas of erosion and deposition along the margin changed dramatically (Berger and Wefer, 1996).

4.4.3 Identification of unconformities formed by currents

Currents create unconformities that can be long, extending along the African margin trending north-south, but relatively narrow, not extending across the margin’s profile. Erosion by bottom currents forms channels that are parallel to the current’s flow direction. The width of the channel depends on the strength and width of the current. Most of the current eroded channels off of West Africa are less than five kilometers wide. If large enough, a current could cause erosion across a margin’s profile, from the shelf to the base of the slope. This current would have strength over a large range of depths, which is unusual.

The current unconformities can be identified on seismic as the base of channels. Reflectors will abruptly terminate at the edges of the channel. Reflectors under the unconformity may be erosionally truncated, if there is an angle between the deposited layers and the seafloor at the time of erosion. Above the unconformity, reflectors onlap and infill the channel.
4.5 Creation of the Angolan Unconformities- a summary

4.5.1 Interaction of mechanisms - sea-level fluctuations, tectonics, and currents

Above, the three causes of unconformities are discussed as they operate in isolation. In a
gеologic system, the mechanisms of sea-level fluctuations, tectonics, and currents are
interrelated and interact. Changes in sea-level affect both tectonic activity and current
flow. Tectonics can influence relative sea-level at a regional and local scale. Changes in
current patterns can force sea-level to rise or fall. Along the Angolan margin, these three
unconformity creating mechanisms have not functioned separately but in an integrated
fashion. Together, they are responsible for the unconformities recorded along the West
African margin.

Fluctuations in sea-level can influence both tectonic activity and current patterns. As sea-
level rises and falls, sediment supply to the basin adjusts. Sediment erosion on the
continent increases as the rivers downcut to the base level decrease established by falling
sea-level. Therefore, sediment input to the basin is higher during lowstands than during
highstands of sea-level. The rate of sedimentation and the amount of sediment load
controls the movement of the salt layer. Therefore, the sea-level indirectly drives the salt
tectonic activity in the basin. Sea-level changes can also drive adjustments in current
patterns. For instance by dropping sea-level below a shelf break, the currents would be
forced to adjust to missing a relatively shallow area of ocean adjacent to the coast.
Changes in tectonic activity do alter sea-level. Only major tectonic events, such as the breakup of Pangea, affect worldwide sea-level. Local tectonic activity does influence relative sea-level. Decreasing the rate of subsidence allows relative sea-level to rise. While increasing subsidence promotes a fall of relative sea-level.

Ocean circulation patterns control the flow of water bodies of various temperatures and conditions. The Present circulation in the Atlantic Ocean directs heat transport around the world. A change in current patterns could alter the heat transport. Adjustments to the heat system would either increase or decrease temperatures around ice sheets encouraging melting or growth. By directing the heat system of the oceans, the currents can raise and lowering sea-level.

Sea-level fluctuations, tectonics, and currents can drive each other, but they can also enhance each other. An unconformity created primarily by sea-level will be enhanced by salt tectonic activity. A change in sea-level coupled with a reorganization of current patterns will create a more significant unconformity. The interaction of erosional and non-depositional mechanisms are recorded in the geologic record of the Angolan margin.

4.5.2 Which mechanisms created the Angolan unconformities

Unconformities identified in the Angolan basins can be linked to their forming mechanisms. The major sequence boundaries (SB1, SB2, SB3) have been dated through correlation with DSDP cores and seismic. These dated unconformities can be assigned
forming mechanisms with confidence. The other sequence boundaries, identified within
the major sequences, can not be dated with certainty. Therefore, their forming
mechanism can only be speculated. The higher order sequence boundaries interpreted on
detailed sequence stratigraphic analysis can be linked to sea-level. The timing of these
unconformities match the rate of sea-level fluctuations.

The earliest of the major sequence boundaries, SB1, is dated as 90 Ma during the
Turonian of the Late Cretaceous. The age of SB1 matches with a major sea-level fall
identified by Hardenbol et al. (1998). No significant development in ocean circulation
occurs around 90 Ma. The thermal subsidence of the margin did slow during the
Cenomanian and Turonian. This change in tectonic activity would only have decreased
the relative sea-level signal compared to eustasy. Therefore, sea-level is concluded to be
the sole mechanism for the creation of SB1.

SB2 is correlated to the 30 Ma unconformity of the middle Oligocene. The 30 Ma
unconformity is recognized worldwide. Due to the worldwide nature of the
unconformity, the primary forming mechanism must be sea-level or ocean circulation
changes. Tectonics may enhance the unconformity. The continent of Africa was uplifted
relative to the rest of continents at least since the Miocene, perhaps beginning in the
Eocene. A significant change in the rate of uplift may have contributed to the erosion
associated with SB2. SB2 is the result of the onset of ice growth and the establishment of
pole to equator climatic gradients. These two events caused a major drop in sea-level and
the onset of intensified bottom currents along the West African margin. The combination of the sea-level fall and circulation change created the major sequence boundary, SB2. The unconformity may have been enhanced by salt tectonics which were triggered by the increased sediment supply to certain areas and the erosion of massive amounts of sediment in other areas.

The latest major sequence boundary of the Angolan basins, SB3, is correlated with an age of 10.5 Ma, Late Miocene. This unconformity is most likely the result of a combination of sea-level fall, current change, and salt tectonics. A major sea-level fall is identified by Hardenbol et al. (1998) at 10.5 Ma. The formation of the NADW and the AABW is dated at about 10 Ma. These two water bodies significantly altered the Atlantic circulation by making the South Atlantic a thoroughfare that transports warm water to the North Atlantic and circulates the cold water out of the North Atlantic. While the sea-level drop and circulation changes alone can create SB3, salt movement also enhances the unconformity. During the Tertiary, salt tectonic activity influences the deposition and erosion of sediment within each of the Angolan basins. The combined forces of the sea-level drop, current changes, and salt tectonics created SB3.

In addition to the major sequence boundaries, SB1, SB2, and SB3, there are several sequence boundaries within each of the basins that were not confidently correlatable between basins. These sequence boundaries are interpreted as unconformities within the
major sequences. While the ages of these unconformities are not known, estimates are made based on the timing of significant changes in sea-level, tectonics, or currents.

Within MS 2, two sequence boundaries are interpreted in each of the three Angolan basins. Between 90 and 30 Ma, the time span of MS 2, several sea-level, tectonic, and current events may have created the two sequence boundaries. At 39.5, 49.5, 58.5, 68, and 80 Ma, Hardenbol et al. (1998) interpret major sea-level falls. At about 40 Ma, Berger and Wefer (1996) notes the change of circulation in the Atlantic. The subsidence rate along the margin slows at about 60 Ma (Poag and de Graciansky, 1992). Any of these events or a combination may be responsible for the unconformities within MS 2.

Within MS 3, two sequence boundaries are interpreted in the Lower Congo and Kwanza Basins and four sequence boundaries are interpreted in the Benguela Basin. Hardenbol et al. (1998) records medium and major sea-level drops at 15.5, 16.5, 21, and 25.5 Ma. A change in circulation is stimulated by the growth of a major ice cap on Antarctica and the formation of the pre-AABW at about 14 Ma (Berger and Wefer, 1996 and Uchupi, 1992). Hardenbol et al. (1998) also note a minor sea-level drop at 13.8 Ma. Any of these events or a combination may be responsible for the unconformities within MS 3.

Within MS 4, one sequence boundary is interpreted in the Kwanza and Benguela Basins and four sequence boundaries are found in the Lower Congo Basin. Medium sea-level falls are recorded at 0.8, 1.6, 2.4, 3.0, 3.8, and 5.5 Ma (Hardenbol et al., 1998). In
addition to the sea-level fall, circulation patterns change at about 3 Ma (Berger and Wefer, 1996). Any of these events or a combination may be responsible for the unconformities within MS 4.

The additional sequence boundaries were interpreted by detailed seismic stratigraphic analysis in each of the three basins. The unconformities found by this detailed analysis are formed at an average rate of one per two to three million years. The relatively short time span between the unconformities suggested that the primary mechanism of formation was sea-level falls. Both changes in currents and tectonics do not occur on this rapid frequency. Therefore, while some of the unconformities may be due to current changes or tectonic events, the majority is assumed to be created by sea-level falls.

4.6 Conclusion

The unconformities interpreted along the Angolan margin illustrate characteristics of each of the mechanisms. The majority of the unconformities is the result of sea-level falls. Many of the sea-level formed unconformities are enhanced, but not driven, by salt tectonic activity. Other unconformities are the product of a combination of sea-level, changes in currents, and tectonics. None of the unconformities can be confidently linked to a tectonic event or change in currents that is not also associated with some amount of sea-level fall. Relative sea-level controls the formation of unconformities.
CHAPTER 5 - STRATIGRAPHIC TIMING OF SALT DEFORMATION

5.1 About salt tectonics

The interaction of salt movement and sedimentation in the Angolan basins is illustrated on geological profiles of the margin. If there were no salt layer, the Angolan margin would resemble a passive margin with sequence stratigraphic patterns closely matching the sequence stratigraphic depositional model of Vail at el. (1977). The complexity of the stratigraphy of Angola is due to the salt tectonics.

The development of salt structures and sedimentary minibasins is controlled by both the initial thickness of the salt layer and the subsequent rates of sedimentation and subsidence. Thus over time the evolution and structural development is influenced by salt.

Due to clear seismic imaging and along dip and strike variations, the Angolan margin provides an excellent opportunity to study the interaction of salt and sedimentation. Studying the sediment/salt interaction offshore Angola allows us to build on the previous salt tectonic studies.

Jackson (1997) recognizes three eras in the development of understanding salt tectonics, the Pioneering Era, the Fluid Era, and the Brittle Era. During the Pioneering Era, 1856 to 1933, a variety of hypotheses were made for salt diapirism. The concepts of
downbuilding and differential loading were introduced. The effects of buoyancy and orogeny were debated. The Fluid Era, 1933 to 1989, began with Nettleton (1934) investigating the fluid mechanics of salt. During this era, salt tectonics was viewed as the result of Rayleigh-Taylor instabilities. A fluid salt layer is displaced upward by a denser fluid overburden having negligible yield strength sinking into the salt. Jackson’s Brittle Era, 1989-present, approached salt tectonics as a system involving a strong, brittle, fractured overburden rather than a weak, fluid one (Jackson, 1997).

This brittle approach explains the interaction we interpret between the salt movement and sedimentation. As the overburden changes the impact on the salt structures changes. The strata surrounding a salt structure records the history of the salt flow. Trusheim in 1957 and 1960 made the first systematic attempt to use the lateral thickness changes in strata deposited during salt flow to determine when the salt was flowing laterally (Jackson, 1997). Using the Trusheim’s principle of using the sedimentary record to infer the history of salt movement, interpretation of the Angolan margin improves our understanding of salt tectonics.

Two models for salt structure development are currently debated amongst geologists. One model supports the active piercement or emplacement of salt into overlying sediments. The other model describes the formation of salt structures by the downbuilding of sediments. The difference between the models is whether the salt moves up or the sediments sink down. The active piercement model developed from
buoyancy theories of Lachmann (1910) and Arrhenius (1913). The buoyancy theories proposed that salt was driven upward like a rising oil drop by the sinking of a denser fluid overburden (Jackson, 1997). Active piercement is post-depositional diapiric growth as suggested by Nettleton in 1934 (Figure 5.1). The diapir increases in relief by growing upward, while its base remains at a constant depth below the sedimentary surface and its crest rises toward the sedimentary surface (Jackson and Talbot, 1991). In 1933, Barton proposed an alternative theory, downbuilding (Figure 5.1). In the Barton’s downbuilding theory, a diapir grew syndepositionally downward from a relatively shallow, static crest. The diapir’s crest remains at or near the surface of sedimentation while its base sinks along with the surrounding, subsiding strata (Jackson, 1997). Neither the active piercement nor downbuilding theories can explain all of the features found in the Angola and other salt basins. The active piercement theory does not overcome the severe mechanical difficulties required for diapiric piercement through thick, strong overburden. The downbuilding theory can not explain the variation between the rate of diapir rise and sediment aggradation. A combination of the two models is likely, with a higher portion of the downbuilding rather than piercement.

The variations along dip and strike profiles provide an understanding of the dominant factors in salt/sediment interaction. Due to the westward tilting of the margin, extensional and contractional elements are present. The style of salt/sediment interaction changes in the different tectonic regimes. The Angolan margin provides a region that has considerable variation of initial salt thickness and subsequent sedimentation along strike.
Figure 5.1: Active piercement and downbuilding salt models. Nettleton (1934) suggested that the salt was driven upward like a rising oil drop by the sinking of a denser fluid overburden. The salt diapir develops post-depositional (1 to 12). Barton (1933) proposed that salt diapirs grew syn-depositionally downward from a relatively shallow, static crest while its base sinks along with the surrounding, subsiding strata (Jackson, 1997).
When comparing the differences in the evolution of the three Angolan basins, other factors can be assumed constant and the effects of the different salt thickness and sedimentation history can be focused on. Interpretation of the Angolan margin is changing our understanding of salt tectonics (Duval et al., 1992; Lundin, 1992; and Spathopoulos, 1996; and Marton et al., 2000).

5.2 Variation along profiles

A typical east-west profile of the Angolan margin can be classified into three regions. Each of these three regions contains different sediment/salt structures. From east to west, the regions are the extensional platform, salt withdrawal minibasins, and contractional folds and thrusts (Figure 5.2). The variations of sediment/salt structures along the margin's profile is due to the initial salt layer, westward tilting of the margin, and sediment supply.

The extensional platform spans the shelf and slope of the Angolan margin. Westward tilting beginning in the Late Cretaceous caused the extension in this region. The initial Aptian salt layer was deposited over syn-rift deposits with relatively uniform thickness across this area. Albian shallow water carbonate deposits formed over the salt. The westward tilting in the Late Cretaceous allowed the carbonate to slide downdip on the salt and break up into blocks, called rafts (Figure 5.9). The subsequent clastic deposition enhanced the separation of rafts and faulting by loading (Duval et al., 1992).
Figure 5.2: The salt/sediment interaction offshore Angola has produced a profile with three distinct regions. The easternmost region is the extensional platform. The central region is the salt withdrawal minibasin area. The westernmost region is the contractional fold and thrust area. These regions are present in each of the offshore basins. This profile developed due to the margin's geologic evolution from a large salt basin that experienced westward tilting and large volumes of sediment input from the coast (modified from Marton et al, 2000).
The salt withdrawal minibasins in the middle regions of the margin contain a variety of styles. The even fill basins (Figure 5.12), asymmetric fill basins (Figures 5.15 and 5.16), pillows (Figure 5.19), and turtles (Figure 5.22 and 5.23) represent some of the sediment/salt structures of the salt withdrawal minibasin area. Within this zone, the evolution of each minibasin is determined by the interplay of various factors. As rates of sediment influx, extension/contraction, and salt movement vary, the depocenters will be affected. These three governing factors are not independent. As sedimentation increases, salt movement increases, the updip extension increases, and the compression downdip increases, and so on. Some of the sediment/salt styles in this salt withdrawal area evolve from each other. Thus as proposed by Trusheim (1957, 1960), pillows precede the formation of turtles. When exposed to contractional forces a minibasin may remain symmetrically filled, when it still is underlain by a thick salt layer. But with an evacuated salt layer, or initially thin salt layer, the older strata will be rotated creating an asymmetric fill basin.

The western region of the Angolan margin is the contractional fold and thrust area. The contraction at the western end of the margin compensates for the extension in the extensional platform and within the salt withdrawal minibasins. The contraction is accommodated by thrust faults and folded strata. The compressional fold and thrust region contains the thickest and most massive salt body of this region (Figures 5.25 and 5.26). Some thrusting is observed within the massive salt body. Folding of the strata overlying the massive salt is common. Squeezed basins are distributed within the
contractional fold and thrust zone. The contractional forces of the sedimentary layers sliding down slope and reaching the toe of that slope produce the contractional synclines.

5.3 Variation between basins

Sediment/salt structures vary from north to south between the Lower Congo, Kwanza, and Benguela Basins. Some of the differences in structures are probably the result of a varying initial salt layer thickness and subsequent sediment input to the basins. The thickness and distribution of the salt determines what types of structures will form. The volume and distribution of sediment input determines the load placed on the salt.

From a regional perspective the differences amongst the basins are evident (Figures 5.3 and 5.4). The Lower Congo Basin, due to a thin initial salt layer and high sedimentation rate during the Tertiary, contains isolated salt diapirs and canopies and a relatively small outboard salt mass. The Kwanza Basin, having a thicker initial salt layer and relatively low subsequent sediment input, has linear salt structures as well as a large mass of salt outboard. The Benguela Basin, with the largest initial salt thickness and fair sediment input, developed complex structures cored with large amounts of salt and a massive outboard salt province.

The initial distribution and thickness of the Aptian Loeme salt is a critical factor for the evolution of the Angolan basins. Figure 5.5 is a conceptual block diagram of the salt basin during the salt deposition. The colored contours on the top of the block diagram
Figure 5.3: Salt tectonic map of the offshore Angolan basins, the Lower Congo, Kwanza, and Benguela. The location of transects A, B, and C (Figure 5.3) are noted by black lines. (modified from Marton et al, 2000)
Figure 5.4: Depth converted transects LC 2, K 4, and B 2 are displayed with vertical exaggeration of 1:7. The location of the transects is noted on figure 5.2. The Aptian salt is green. The blue layer is Late Cretaceous deposits including the Pinda formation. The blue layer is the first major sequence of the post-salt section (MS 1). The orange layer is Late Cretaceous to Oligocene deposits including the labe and Landana formations. The orange layer is MS 2. The yellow layer is the Oligocene to present deposits including the Malembo formation. The yellow layer includes both the MS 3 and MS 4.
Figure 5.5: Conceptual diagram of the salt basin during the Aptian salt deposition. The diagram shows thicker salt deposits to the south. The salt thins to the north and toward the coast. Rift grabens and faults affect the thickness of the salt layer.
represent a salt isopach map during deposition. Overall, the salt layer thins toward the north. If rift grabens along the Angolan coast were not completely filled by syn-rift and post-rift sediments prior to salt deposition, then they could provide varying amounts of accommodation space that were filled by the salt. Thus the rift graben geometries could be related to potential initial salt thicks and thins. Initial salt thicks versus thins develop into different salt structures as the basin evolves.

The sediment input to the Angolan basins is illustrated by a free-air gravity map based on satellite data (Figure 5.6). The semi-circular gravity high offshore the Congo River to the north is due to the large sediment volume deposited in the Lower Congo Basin. The Tertiary sediment input is greatest off of the Congo River and decreases toward the south, through the Kwanza Basin, before increasing again in the Benguela Basin. The input of large volumes of clastics from the Congo River have influenced the evolution of sedimentary minibasins and salt structures in the Lower Congo Basin. The elongated gravity high along the coast of Angola may follow the trend of deeper rift grabens. The rift grabens may have influenced the initial deposition and thickness of the Aptian salt layer.

With different initial salt thickness and subsequent volumes of sediment, the three Angolan basins developed different salt tectonic patterns.
Figure 5.6: Free air gravity map based on satellite data from
Sandwell and Smith, 1997. Version 9.2 was used to generate
the free-air gravity map. The unit of the color scale is mGal.
The large sediment volume deposited by the Congo River into
the Lower Congo Basin is indicated by the semi-circular gravity
high. The gravity high that follows the coast of Angola may
follow the trend of the rift grabens (Sandwell and Smith, 1997).
5.4 Specific sediment/salt features

Across and along the Angolan margin a variety of sediment/salt structures have developed. These sediment/salt features are not unique to Angola. They can be found in salt basins around the world. Angola does provide clear seismic images of the sediment and salt that allow for improved understanding of the structures' geological evolution.

5.4.1 Rafts and pre-rafts

The Kwanza Basin is the type locality for raft tectonics. Shallow water carbonates were deposited on the Aptian salt. Westward tilting caused the carbonates to become faulted and slide on the salt. Gravity sliding is the downslope sliding of an overburden sheet or block under its own weight over a weak, ductile decollement (Jackson and Talbot, 1991). As the extensional forces of gravity sliding continued, the Albian carbonates broke into rafts. The break up created accommodation space between the separating pre-raft sequence and the subsequent depocenters that were controlled by the faults. The loading of sediments added the force of gravity spreading to the gravity sliding, continuing to create additional local accommodation space (Figure 5.7). Gravity spreading is the vertical collapse and lateral spreading of salt and any overburden under their own weight (Jackson and Talbot, 1991). The raft domain is located in the Kwanza Basin below the present shelf and slope (Figure 5.8). Hydrocarbons can be trapped in structures within the rafts due to rotation of strata. Depocenters between rafts trap reservoir quality sediments. Raft tectonics provides a mechanism for transporting shallow water, reservoir quality deposits into the deep-water realm. Figure 5.9 is a seismic example from the
Figure 5.7: Diagrams of raft development. Shallow water carbonates (blue) were deposited over the Aptian salt layer (green). Tilting of the margin and additional sedimentation (yellow) initiated gravity sliding and spreading. The subsequent sediments preferentially deposited along the faults creating depocenters. The ‘folding’ of the top yellow is due to differential compaction and fault movement.
Figure 5.8: The distribution of rafts and pre-rafts is identified in grey. The location of the seismic example of pre-rafts is noted by a black dot (Figure 5.9).
Figure 5.9: Seismic section with pre-rafts of the Kwanza Basin. The salt layer is highlighted in grey. The faults and some horizons are identified by black lines.
Kwanza Basin. The rotated blocks of Albian carbonate and overlying clastic depocenters are clearly imaged.

5.4.2 Evenly-filled (ponded) basins

Sedimentation over the salt, created highs and lows on the surface of the salt. Once established, the sediment flows moved around the salt highs and deposited sediment between them in minibasins. The sediment filled these basins evenly, onlapping the salt at the edges. The even basin fill continued until either the sediment flow volume overwhelmed and covered the salt highs, or the salt layer depleted though withdrawal and was no longer capable of maintaining the highs (Figure 5.10). The evenly-filled basins are located in each of the basins offshore Angola. They are distributed in a band outboard of the raft domain and inboard of the massive salt (Figure 5.11). Figure 5.12 is a seismic example from the Kwanza Basin. The seismic shows the reflectors converging updip and onlapping the salt structures.

5.4.3 Asymmetric fill basins

Due to differences in the relative rates of sedimentation and salt withdrawal, the minibasin is often asymmetrical. There is a sensitive interplay between sedimentation and salt movement. As the load on the salt increases by adding sediment, salt withdrawal increases. When the rate of sedimentation decreases, the salt withdrawal decreases. When examining the salt/sediment interaction, a three dimensional perspective is required. Figure 5.13 illustrates the evolution of a minibasin with asymmetric fill. At
Figure 5.10: Diagrams of the development of evenly-filled (or ponded) basins. The sediments preferentially deposit over the salt lows (or thins). The minibasins between the salt highs are filled evenly. If the sediment volume overwhelms the salt highs or the salt layer becomes depleted, then the sediment is deposited across the highs, between the minibasins.
Figure 5.11: The distribution of evenly-filled minibasins is identified in grey. The location of the seismic example of evenly-filled minibasins is noted by a black dot (Figure 5.12).
Figure 5.12: Seismic section with evenly-filled minibasins of the Kwanza Basin. The salt layer is highlighted in grey. The faults and some horizons are identified by black lines. The salt structures are pillows.
first, the basin is symmetric, receiving sediment from flows meandering downslope. Due to a change in a sediment pathway, the right side of the basin receives more sediment. The salt withdraws from the right side of the basin, accommodating the additional load. The sediment focus shifts to the left side of the basin with preferential loading and withdrawal. The subsequent sedimentation and salt movement rotate the underlying strata. Asymmetrical filled minibasins are found in each of the three basins offshore Angola. These minibasins are distributed in a band, outboard of the shelf and raft domain and landward of the massive salt domain (Figure 5.14). Each of the seismic examples (Figures 5.15 and 5.16) shows variations of sediment focusing through time due to salt withdrawal. Figure 5.15 displays the high degree of rotation and onlap that result from salt movement in the minibasins. Figure 5.16 has a lower degree of strata rotation, but has an added complication of various levels of salt structures surrounding a minibasin.

5.4.4 Pillows

The term pillow refers to a salt structure. A pillow is a near-circular structural mound of salt. Salt pillows form at various scales. Figure 5.17 shows how salt structures may initiate pillow formation. In the upper diagram, two shallow salt diapirs influence the seafloor topography. Even a slight change in gradient can influence the flow of sediment. As the sediment moves around the shallow salt structures, it deposits preferentially in the areas pointed to by arrowheads. Since these areas receive more sediment, the load on the salt is greater at these points. The lower diagram shows how the salt has withdrawn from the areas with higher sedimentation rates, creating adjacent salt pillows. Salt pillows are
Figure 5.13: Diagrams of the development of an asymmetric basin. The yellow arrows indicate sediment flow pathways. The green arrows display the salt withdrawal directions. The basin begins as an evenly-filled basin. The change in the direction of the sediment source alters the balance between the salt movement and sedimentation. Salt withdraws from the right side of the basin due to the sediment load. The sediment onlaps the salt on the right side. Due to a change in sediment flow, the left side of the basin experiences preferential sediment loading and salt withdrawal. The underlying strata are rotated and the subsequent sediment onlaps the earlier strata.
Figure 5.14: The distribution of the asymmetric minibasins is identified in grey. The locations of the seismic examples of an asymmetrically filled minibasins is noted by a black dot (Figures 5.15 and 5.16).
Figure 5.15: Seismic example of an asymmetrically filled minibasin of the Benguela Basin. The salt layer is highlighted in grey. The faults and some horizons are identified by black lines.
Figure 5.16: Seismic example of an asymmetrically filled minibasin of the Kwanza Basin. The salt layer is highlighted in grey. The faults and some horizons are identified by black lines.
the first step in the development of several sediment/salt structures, including turtles as described below. Once established, salt pillows can have a dominant control over sediment pathways. However, once sedimentation rates become high enough or the supporting salt layer evacuates the pillows will be buried. The pillows occur in a wide band outboard of the shelf and raft domain and landward of the massive salt domain. Pillows are found in each of the Angolan basins (Figure 5.18). Figure 5.19 illustrates a pillow approximately 10 kilometers wide. Figure 5.12 shows pillows that are a couple of kilometers wide.

5.4.5 Turtles
The term turtle refers to strata which develops the shape of a turtle shell. The evolution of a turtle is shown in block diagrams (Figure 5.20). At the beginning of turtle development, sediment flows around salt highs and deposits in the surrounding lows. Therefore, the areas between the salt highs become depocenters receiving thick layers of sediment and sediment layers thin onto the salt highs. As the salt layer evacuates, the salt highs can no longer keep up with sedimentation and stop growing taller. Sediment flows are no longer dictated by salt based topography. As the salt continues to withdraw, the areas on top of the old salt highs become depocenters. The focus of deposition shifts from between the salt highs to on top of the old salt highs. At the base, a turtle has layers thickening toward its center. On top of these layers, a turtle may contain layers with constant thickness. Overlying the turtle, layers will thin over the turtle's back. Turtle interpretation provides understanding of sediment pathways through time. Turtles are
Figure 5.17: Diagrams of the development of pillows. The yellow arrows indicate the sediment flow pathways. The dashed circles are the location of salt diapirs. The flow of sediment is affected by the surface expression of the salt diapirs. The sediments flow around the diapirs, preferentially loading certain areas. Salt withdrawal increases beneath these areas. The areas in the shadow of the diapirs receive less sediment and therefore have less salt withdrawal. Under these shadow areas pillow develop.
Figure 5.18: The distribution of pillows is identified in grey. The location of the seismic example of a pillow is noted by a black dot (Figure 15.19).
Figure 5.19: Seismic example of a pillow in the Kwanza Basin. The salt layer is highlighted in grey. The faults and some horizons are identified by black lines.
present in each of the three basins, but restricted to a narrow band just west of the shelf and slope (Figure 5.21). Figure 5.22 is a seismic example of a turtle between two diapirs in the salt withdrawal minibasin region of the Lower Congo Basin. Figure 5.23 displays a turtle at the base of the slope in the Kwanza Basin.

5.4.6 Squeezed Basins

The westward sliding of sediments and the deformation of salt is also associated with contracted synclinal basins. The initial deposition is even fill between salt highs. As the westward tilting and downslope forces increase, the salt highs grow and are squeezed closer together. The previous deposits between the salt highs are rotated. The new sediments are preferentially deposited on the up-slope side of the minibasins. These minibasins are asymmetrical because of the added load due to reverse faulting. Unconformities form within the minibasin sediments by variations in the relative rates of salt movement and sliding or sedimentation. The salt layer supporting the salt diapirs or walls becomes depleted forming welds. During a period of decreased sedimentation relative to the westward forces, the salt may form salt tongues that amalgamate to canopies (Figure 5.24). The squeezed basins are distributed within the Lower Congo and Kwanza Basins, east of the massive salt domain and west of the pillow and turtle domains (Figure 5.25). Figure 5.26 shows squeezed basins in the salt withdrawal minibasin region of the Lower Congo Basin. The salt diapirs between the minibasins are tilted westward and the sediments indicate thrusting along the salt.
Figure 5.20: Diagrams of the development of turtles. The yellow arrows indicate the sediment flow pathways. The dashed circles are the locations of underlying salt diapirs. The development begins with pillows and evenly-filled minibasins. As the salt layer deflates, the sedimentation covers the highs and lows of the salt layer. As the old highs deflate, the sediment is preferentially deposited over the old salt highs.
Figure 5.21: Distribution of turtles is identified in grey. The locations of seismic examples of a turtle are noted by black dots (Figures 5.22 and 5.23).
Figure 5.22: Seismic example of a turtle in the Kwanza Basin. The salt layer is highlighted in grey. The faults and some horizons are identified by black lines.
Figure 5.23: Seismic example of a turtle in the Kwanza Basin. The salt layer is highlighted in grey. The faults and some horizons are identified by black lines.
Figure 5.24: Diagrams of the development of squeezed basins. The yellow arrow indicates the sediment flow direction. The evolution begins with evenly-filled minibasins and pillows. As basin tilting and downslope movement increases, the salt highs grow and are squeezed closer together. The strata in the minibasins are rotated. Subsequent sediment onlaps the rotated strata. The salt may form downdip flowing canopies.
Figure 5.25: The distribution of the squeezed minibasins is identified in grey. The location of seismic example of the squeezed basins is noted by a black dot (Figure 5.26).
Figure 5.26: Seismic example of squeezed minibasins in the Kwanza Basin. The salt layers are highlighted in grey. Faults and some horizons are identified by black lines.
5.4.7 Massive salt

In each of the basins, the western third is a massive salt feature (Figure 5.27). The massive salt is allochthonous and structurally thickened from its original size. The thickening is due to the contraction. The extension of the shelf and slope region is compensated by contraction at the edge of the salt basin. In addition to thickening, the salt body has moved farther west than its original salt basin. Figure 5.28 shows a typical massive salt body that is several kilometers thick. On some of the seismic profiles, thrust faults are visible within the massive salt body. Figure 5.29 is a seismic example of the massive salt with some indication of thrust faults. The imaging of the thrusts may be due to the incorporation of sediments within the massive salt body during contraction. Another interpretation of these salt structure is that the salt is not massive, but an allochthonous salt mass with underlying sedimentary strata.
Figure 5.27: The distribution of the massive salt is identified in grey. The locations of seismic examples of the massive salt are noted by black dots (Figures 5.28 and 5.29).
Figure 5.28: Seismic example of the massive salt in the Benguela Basin. The salt layer is highlighted in grey.
Figure 5.29: Seismic example of the massive salt in the Kwanza Basin. The salt layer is highlighted in grey. Faults are identified by white lines.
CHAPTER 6 - SUMMARY

6.1 Introduction

This seismic sequence stratigraphic study examined three offshore basins of Angola, west Africa. The dataset included a 2D regional reflection seismic grid and well data from the Deep Sea Drilling Program (DSDP) Site 364 (Bolli and Ryan, 1978). The reflection seismic data was interpreted using seismic stratigraphic interpretation techniques. The well data was used to constrain the ages of the interpreted seismic horizons.

The active tectonic and depositional history of the Angolan margin make it an excellent study area for examining the factors that control the deposition and preservation of sediments in sequences, as well as the factors that create the erosion or non-deposition along sequence boundaries. Since the seismic data grid covers an area of about 300 by 850 kilometers (255,000 km²), the entire shelf to abyssal plain profile was interpreted along various transects in each of the three offshore basins. The sequences of each transect were compared to understand which factors dominate the geologic evolution of the sequences. Using the age constraints of the DSDP site data, the Angolan sequences can be compared to global sequence charts and used to investigate the effects of local events versus global events on the area's sequences.

This study accomplished several objectives. The tectonic evolution of the Angolan margin was reviewed. The sequence stratigraphic framework of Angola was established.
The sequences were compared with the global sequence charts as well as with events that are global, regional, and local. These events included sea-level changes, tectonic events, and changes in oceanic circulation. The formation of the sequence bounding unconformities was examined. Within the sequences, the interaction of sedimentation and salt movement was described. In this chapter the results from work on each of these objectives is summarized.

6.2 Evolution of the Angolan margin

The geological evolution of the Angolan margin is based on geological and geophysical data from local, regional, and global sources. The basin evolution is traced back to the supercontinent of Pangea. The Pan African/Brasiliano orogeny formed the metamorphic basement of the Angolan basins formed during the beginning of the Phanerozoic Phanerozoic (Burke et al., 1977; Kroner, 1980; and Gerrard and Smith, 1982). During the Jurassic, the initiation of the breakup of Pangea and the formation of the Atlantic Ocean began with regional uplift and volcanism associated with the rupture of the continental crust (Emery and Uchupi, 1984 and Standlee et al., 1992). The breakup began at the southern end of Pangea and migrated to the north (Nurnberg and Muller, 1991). In the Angolan basins, lacustrine deposits were formed during the rifting stage in the Jurassic and Early Cretaceous (Brice et al., 1982; McHargue, 1990; Henry et al., 1995; and Braccini et al., 1997). Oceanic crust was implaced along the mid-oceanic ridge. As marine waters formed the early ocean, physical barriers restricted the flow of
the saline waters. In the Aptian, salt layers formed (Belmonte et al., 1965; Pautot et al., 1973; Burke, 1975; Evans, 1978; de Ruiter, 1979; and Hardie, 1990).

Once the marine incursion was established, a margin section developed along the basins as a result of thermal cooling and subsidence. Shallow water carbonate developed during Albian time (Brognon and Verrier, 1966; Tillement, 1987; Walgenwitz et al., 1990; and Ala and Selley, 1997). Sea-level fluctuated throughout the Late Cretaceous to present, influencing development of the Angolan margin. Clastic deposits covered the shallow water carbonate along with westward tilting of the margin (Gerrard and Smith, 1982; Platt et al., 1993; Ala and Selley, 1997; and Marton et al., 2000). The combination of the sedimentation and the tilting, stimulated the movement of the salt layers (Duval et al., 1992; Lundin, 1992; and Maudit et al., 1997). Subsequent deposition was influenced by, and in turn influenced, the development of salt structures Baumgartner and van Andel, 1971; Kneller and McCaffrey, 1995; and Spathopoulos, 1996). An interplay of salt movement and sediment deposition dominated the Tertiary development of the basins. The uplift and erosion of Africa also provided a source for and influences on the Tertiary sedimentation (Bond, 1978; Sahagian, 1988; Lunde et al., 1992; and Nyblade and Robinson, 1994).

Ocean circulation developed aggressively in the Cenozoic (Uchupi, 1992). Thermohaline circulation and abyssal circulation developed between the Middle Eocene and Late Oligocene (Uchupi, 1992). Three significant circulation changes occurred during the
Late Eocene, Middle Miocene, and the Late Miocene (Uchupi, 1992; Schmitz, 1995; and Berger and Wefer, 1996). The circulation changes were associated with the movement of continents and the formation of major ice sheets (Uchupi, 1992 and Berger and Wefer, 1996).

6.3 Sequence stratigraphic framework

Four major sequences are identified along the Angolan margin. Additional sequences are identified in the basins, but can not be correlated regionally across all of the offshore basins. The age of the major sequences is estimated by correlating the interpreted seismic sequences with ages from the DSDP site 364. Each of the interpreted major seismic sequence boundaries has an age range that includes a major sequence boundary as published in Hardenbol et al. (1998).

The oldest major sequence (MS 1) deposited over the Aptian salt spans from the end of the Aptian (112.2 +/- 1.1 Ma) to the Turonian (90.0 +/- 0.5 Ma). The second post-salt major sequence (MS 2) was deposited between the Turonian and the Rupelian (30.0 Ma). The third major sequence (MS 3) ranges between the Chattian and Tortonian (10.5 Ma). The fourth, most recent, sequence (MS 4) began in the Tortonian and continues to the present. These four major sequences span time intervals of 10 to 50 My and are considered to be second-order sequences.
Within each of the offshore basins, lower order sequences are interpreted within the major sequences. In the Lower Congo Basin, thirteen third-order sequences are interpreted between the base of MS 1 and the top of MS 4. The Kwanza Basin has only ten third-order sequences within MS 1 to MS 4. In the Benguela Basin, twelve third-order sequences subdivide the major sequences.

Detailed seismic sequence stratigraphic interpretation of the shelf region revealed higher frequency third and fourth-order sequences. The Lower Congo Basin has 42 third to fourth-order sequences between the Late Cretaceous/early Tertiary to Pliocene. During the early Tertiary to Pliocene, the Kwanza Basin developed eleven third-order sequences. The Benguela Basin has 27 third to fourth-order sequences between the Late Cretaceous and the Pliocene.

6.4 Understanding unconformities

This study examined three mechanisms that can create an unconformity – sea-level fluctuations, tectonic activity, and changes in current circulation patterns. Each of these mechanisms creates unconformities with different characteristics. The mechanisms also combine to enhance or detract from each other. The formation of each of the sequence bounding unconformities is related to these mechanisms.

The earliest of the major sequence boundaries, SB1, is dated as 90 Ma (Late Cretaceous), matching a major sea-level fall identified by Hardenbol et al. (1998). No significant
development in ocean circulation occurred around 90 Ma. The thermal subsidence of the margin slowed during the Cenomanian and Turonian. This change in tectonic activity would only have decreased the relative sea-level signal compared to eustasy. Therefore, sea-level is concluded to be the sole mechanism for the creation of SB1.

SB2 is correlated to the 30 Ma global unconformity of the middle Oligocene. Due to the worldwide nature of the unconformity, the primary mechanism is sea-level or ocean circulation changes. Tectonics may have enhanced the unconformity be uplifting the African continent. SB2 is the result of eustatic change associated with the onset of ice sheet growth in Antarctica and the establishment of pole to equator climatic gradients. These two events caused a major drop in sea-level and the onset of intensified bottom currents along the West African margin.

The latest major sequence boundary of the Angolan basins, SB3, has an age of 10.5 Ma (Late Miocene). This unconformity is most likely the result of a combination of sea-level fall, oceanic current intensification, and salt tectonics. A major sea-level fall is identified by Hardenbol et al. (1998) at 10.5 Ma. The formation of the NADW and the AABW is dated at about 10 Ma. While the sea-level drop and circulation changes alone can create SB3, salt movement also enhances the unconformity. The combined forces of the sea-level drop, current changes, and salt tectonics created SB3.
The sequence boundaries of the third to fourth-order sequences can be correlated to sea-level, tectonic, and circulation events. Any of these events or a combination of them may be responsible for the unconformities within the major sequences. The relatively short time between most of the unconformities suggests that the primary mechanism of formation was sea-level falls. Changes tectonics do not occur on a rapid frequency. Changes in ocean current patterns or intensity may occur on the same frequency as eustasy. However, currents alone, without eustasy, are not documented to cause erosion or non-deposition regionally. Therefore, while some of the unconformities may be due to current changes or tectonic events, the majority are assumed to be created by sea-level falls.

6.5 Stratigraphic timing of salt deformation

The Tertiary development of the Angolan margin is strongly influenced by salt tectonics. Variations along dip and strike profiles provide an understanding of the dominant factors in salt/sediment interaction.

The east-west profile of the Angolan margin can be classified into three regions. Each of these three regions contains different sediment/salt structures. From east to west, the regions are the extensional platform, salt withdrawal minibasins, and contractional folds and thrusts. The variations of sediment/salt structures along the margin's profile is due to the initial salt layer, westward tilting of the margin, and sediment supply.
Sediment/salt structures also vary from north to south between the Lower Congo, Kwanza, and Benguela Basins. Some of the differences in structures are the result of varying initial salt layer thickness and subsequent sediment input to the basins. The thickness and distribution of the salt determines what types of structures will form. The volume and distribution of sediment input determines the load placed on the salt.

Across and along the Angolan margin a variety of sediment/salt structures have developed. This study classifies the salt structures and the minibasins into the following categories: rafts and pre-rafts, evenly-filled (ponded) basins, asymmetric fill basins, pillows, turtles, massive salt, and squeezed basins. The timing of the salt deformation and sedimentation is described and illustrated for each of these categories. The complex interplay of sedimentation and salt deformation creates the variation between and along the transects of the Angolan margin.
REFERENCES


APPENDIX A - REVIEW OF UNCONFORMITIES

A.1 Introduction

The term unconformity has been in the geologic vocabulary for over two hundred years. Use of the term has changed as both geologic thinking and understanding have changed. In this study, an unconformity is a time gap in the geologic record due to erosion or non-deposition. Seismic can be used to image unconformities beautifully and while not a direct indicator, seismic contains a great deal of information on the formation of an unconformity. The patterns of the reflectors above and below the unconformity and the termination patterns on the unconformity are the keys to the interpretation of how the unconformity was formed.

The interpretation of unconformities and their formation is crucial to the understanding of the geologic record. An unconformity defines a hiatus between periods of continuous deposition with evidence of erosion or non-deposition. Since unconformities are breaks in the geologic record, they are convenient and logical boundaries for subdividing the record into packages. Unconformities separate stratigraphic units composed of a relatively conformable succession of genetically related strata that are called depositional sequences (Mitchum et al., 1977). The geological development of a margin is understood by separating the geologic record into sequences and then determining the factors active during each sequence and the changes between sequences.
In this appendix, the history of the term unconformity is reviewed. The classification system of unconformities is described. The process of identifying unconformities in seismic data is explained. The pitfalls of seismic interpretation due to data limitations are identified.

A.2 History of the term unconformity

The term unconformity is defined differently through time. The core of its original definition is the concept that an unconformity is a time gap in the geologic record. Hutton in 1788 recognized unconformities as boundaries between cycles of uplift/folding, erosion, and deposition. Over the last two hundred years the concept of unconformity has been elaborated upon and modified. Thoughts on what is the dominant factor controlling the formation of regional and interregional unconformities fluctuate between sea-level changes and tectonics. Suess (1888) attributed the patterns of onlap and offlap, which define unconformities, to changes in sea-level. Suess introduced the concept and term eustatic for worldwide sea-level changes. The concept of eustasy was not accepted as the sole mechanism capable of creating worldwide unconformities. Rather than fluctuations of sea-level, the tectonic movement of land through orogenic folding or epierogenic warping was believed to create unconformities and break up the geologic record. Stille (1924) used major unconformities to subdivide his orogenic cycles into tectonic phases. Levorsen (1943) described the concept of successive layers in the earth separated by an unconformity. Levorsen (1943) suggested that these layers found in the United States would be found over the world. Sloss in 1949 introduced unconformity bounded
packages (sequences) which represented depositional cycles. Tectonics influenced these depositional cycles by controlling the balance between the rate of sediment accumulation and the rate of subsidence. Sea-level was not recognized by Sloss as a control of sedimentation or of accommodation space (Sloss, 1963 and Sloss 1991). Fairbridge (1961) claimed that worldwide sea-level changes were independent of land movement and suggested that tectonic changes might be only local. Fairbridge (1961) linked sequence geometry to eustasy. With advances in seismic imaging, seismic stratigraphy was introduced in 1977. Vail (1977) defined an unconformity as 'a surface of erosion or non-deposition that separates younger strata from older rocks and represents a significant hiatus (at least a correlatable part of a geochronologic unit is not represented by strata).' Van Wagoner et al. (1988) narrowed the definition of an unconformity to 'a surface separating younger from older strata, along which there is evidence of subaerial erosional truncation (and, in some areas, correlative submarine erosion) or subaerial exposure, with a significant hiatus indicated.' The modification of the definition was an attempt to differentiate between sequence and parasequence boundaries. In the history of unconformity debates, the discussion of submarine unconformities was neglected. While both sea-level and tectonics have been at the center of discussions of the creation of unconformities, the impact of submarine currents has not been adequately discussed.

A.3 Classification systems

Conventional unconformity classifications differentiate various types such as disconformities, angular unconformities, and nonconformities (Figure A.1). A
Figure A.1: Types of unconformities. The geometric and depositional relationship of the underlying and overlying strata define the unconformity. The angular unconformity is commonly assumed to be the result of tectonic activity. The tilting of the layers under an angular unconformity is due to tectonic activity. But the structural changes do not erode, a change in sea level provides the mechanism for erosion and the creation of the unconformity. The erosion of strata underlying a disconformity or local unconformity are similarly the result of relative sea level changes. A nonconformity separates igneous and metamorphic rocks from sedimentary layers, erosion is not required. This study examines the creation and significance of angular unconformities, disconformities, and local unconformities (Shell Oil Company, 1987).
disconformity is a time gap within a sequence of sub-parallel layers. An angular unconformity is an erosional surface that cuts across older tilted strata and is overlain by parallel beds. A nonconformity is the contact between sedimentary layers and underlying eroded igneous or metamorphic rocks. Each of these three types of unconformities represents a time gap due to erosion and/or non-deposition. Vail (1977) recognizes the emphasis the conventional classifications place on the angularity or parallelism of the layers above and below the unconformity and suggests using the relation of the strata to the unconformity, since this criterion is more useful in chronostratigraphy. An unconformity can be described as the upper or lower boundary of a sequence. As an upper boundary, an unconformity can be defined by erosional truncation or toplap. Onlap can define an unconformity as a lower boundary of a sequence.

Another classification system defines unconformities by the process that creates them, such as an erosional unconformity or non-depositional unconformity. The event that a surface signifies can be used to name it, for instance a breakup unconformity or drowning unconformity. If an unconformity defines a unit, it may be named, for example, a base or top of the seaward dipping reflectors. The relation between the timing of rifting and deposition may also be used to name unconformities. Such surfaces are called syn-rift unconformities and post-rift unconformities. An unconformity along with its correlative conformity is a sequence boundary. The unconformity may also be referred to by the type of data used to identify it – seismic unconformity or outcrop unconformity. The areal extent of an unconformity is also noted, by local unconformity versus interregional
unconformity. Although unconformities come with a variety of names, the concept of an unconformity as a hiatus in the geologic record and a boundary between packages of rock is common to all definitions. Very little attention is paid to the erosional processes causing the unconformities.

A.4 Identifying unconformities on reflection seismic profiles

On seismic data an unconformity is identified by the patterns of the reflectors above and below the surface and the relation of the terminations to the surface (Figure A.2). Primary seismic reflections are generated by physical surfaces in rocks. These surfaces are mainly stratal (bedding) surfaces and unconformities with velocity-density contrasts. The reflectors below an unconformity may terminate by erosional truncation, down cutting erosional truncation, or toplap. Erosional truncation indicates the deposition of strata followed by tilting and erosion along the unconformity surface. Down cutting erosional truncation implies horizontal strata have been cut into and eroded away. The example shows horizontal reflectors terminating against an erosional surface created by a channel or gorge. Toplap termination of reflectors occurs where non-deposition due to sedimentary bypass and slight erosion has created an unconformable surface. Above an unconformity, reflections terminate by onlap. Onlap termination results either from initially horizontal strata terminating against an initially inclined surface or from initially inclined strata terminating progressively updip against a surface with a greater initial inclination. Subsequent deformation may cause onlapping strata to appear as downlapping onto a surface. Downlap is the termination pattern of inclined reflections
Figure A.2: Terminations of strata on boundaries of depositional sequences. Erosional truncation: strata at the top of a given sequence terminate against an upper boundary mainly as a result of erosion (e.g., tilted strata terminating against an overlying horizontal erosion surface, or horizontal strata terminating against a later channel). The erosion occurs mainly as a result of a drop in relative sea level. Toplap: initially inclined strata at top of a given sequence terminate against an upper boundary mainly as a result of non-deposition (e.g., foreset strata terminating against an overlying horizontal surface at base-level equilibrium where no erosion or deposition took place). Onlap: at the base of a sequence initially horizontal strata terminate progressively against an initially inclined surface, or initially inclined strata terminate updip progressively against a surface of greater initial inclination. Downlap: at the base of a sequence initially inclined strata terminate downdip progressively against an initially horizontal or inclined surface (e.g., initially inclined strata terminating against an underlying initially horizontal surface) (modified from Mitchum et al., 1977).
onto a less inclined or horizontal surface. Downlap does not identify an unconformity surface.

A.5 Limitations of seismic data

The use of seismic data to image unconformities is limited by its resolution (Sheriff, 1977). When seismic models are constructed for known outcrops, the seismic often fails to image unconformities found in outcrop or else displays unconformities not present in outcrop. Resolution is the cause of both discrepancies. Vertical resolution of seismic data is the minimum separation needed between two reflectors to distinguish the two as separate interfaces rather than as a single interface. In ideal cases, the separation is approximately 1/8 to 1/4 of a wavelength. The vertical resolution ranges from a scale of meters to tens of meters depending on the recording frequency. In an outcrop, one has resolution down to hand lens scale. In a seismic profile closely spaced unconformities would not be resolved as separate surfaces. 'Pseudo-unconformities' are the result of seismic record's inability to image rapid changes of dip and facies. In outcrop, the changes of dip and/or facies over a short distance can be detected. When seismic models are constructed for known outcrops, the seismic images the abrupt changes as termination patterns (Figures A.3-A.5) (Stafleu, 1994). Without additional knowledge, these terminations would be used to define unconformities on the seismic profiles. As with any data set, the limitations of seismic data must be appreciated during interpretation.
Figure A.3: a) Lithologic model of the upper part of Picco di Vallandro, northern Italy. Steep carbonate clinoforms prograde from left to right and interfinger with basinal, marly sediments at the toe of slope. b) Seismic model showing the rapid changes in the facies and in dip as downlap and onlap patterns. Figures 4.4 and 4.5 examine the pseudo-onlap and pseudo-downlap of this Picco di Vallandro model (Stafleu, 1994).
Figure A.4: Detail of the lithologic model of figure 4.3. Using 25 Hz, the seismic model shows pseudo-onlap at the toe of slope. With 50 Hz, the interfingerling pattern becomes visible. At 100 Hz, the interfingerling pattern is well displayed. The frequency of the seismic dataset will change the resolution of the image (Staflus, 1994).
Figure A.5: Detail of the lithologic model of figure 4.3. Using 25 Hz, the seismic model shows pseudo-downlap at the toe of slope where the slope progrades. At 50 and 100 Hz, the interfingerling pattern starts to become visible. Even the peak-frequency of 100 Hz is not able to properly resolve the image (Stafleu, 1994).