1990

Geochemistry and Origin of Smackover and Buckner Dolomites (Upper Jurassic), Jay Field Area, Alabama - Florida.

Marshall J. Vinet
Louisiana State University and Agricultural & Mechanical College

Follow this and additional works at: https://digitalcommons.lsu.edu/gradschool_disstheses

Recommended Citation
https://digitalcommons.lsu.edu/gradschool_disstheses/4958

This Dissertation is brought to you for free and open access by the Graduate School at LSU Digital Commons. It has been accepted for inclusion in LSU Historical Dissertations and Theses by an authorized administrator of LSU Digital Commons. For more information, please contact gradetd@lsu.edu.
INFORMATION TO USERS

The most advanced technology has been used to photograph and reproduce this manuscript from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps. Each original is also photographed in one exposure and is included in reduced form at the back of the book.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.
Geochemistry and origin of smackover and Buckner dolomites (upper Jurassic), Jay Field area, Alabama - Florida

Vinet, Marshall J., Ph.D.

The Louisiana State University and Agricultural and Mechanical Col., 1990
GEOCHEMISTRY AND ORIGIN OF SMACKOVER AND
BUCKNER DOLOMITES (UPPER JURASSIC),
JAY FIELD AREA, ALABAMA - FLORIDA

A Dissertation

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

in

The Department of Geology and Geophysics

by
Marshall J. Vinet
B.S., University of New Orleans, 1971
M.S., University of New Orleans, 1975
May, 1990
ACKNOWLEDGEMENTS

I gratefully acknowledge Dr. Clyde H. Moore, who served as major professor, for his support, guidance, patience and most of all, his and his wife Marlene's friendship over the years. Drs. George Hart, Dag Numedal, Harry Roberts and Joseph Hazel served as committee members and provided helpful suggestions for improving the manuscript. Dr. Vijay Singh (Civil Engineering) served as a sixth reader which was greatly appreciated. I was most fortunate to work with Drs. Yehezkeel "Charlie" Druckman, Eytan Sass, Tony Dickson, and Gill Harwood, who participated in the on-going Applied Carbonate Research Program (ACRP). Special thanks to Dr. Eytan Sass (Hebrew University of Jerusalem) who taught a wet nosed kid lab techniques for AAS analysis, and how to play squash. A very special thanks go to Charlie Druckman (Geological Survey of Israel) from whom I have learned petrology, stratigraphic analysis, geochemical insight and the meaning of life. Tony Dickson and Gill Harwood contributed greatly to my understanding of stable isotopes. Many thanks to the participants of the ACRP for their many constructive comments at the annual meetings. I am particularly thankful to Dick Koepnick and the Mobil Research Department for the radiometric Sr analysis of the upper and uppermost Smackover dolomites. I appreciate Mike Stamatedes, Dr. Ezat Heydari, Dr. Art Saller, Mary Jo Klosterman, Kevin Cunningham and other fellow graduate students for their friendship and helpful discussions. Art and Julie Saller provided shelter during my last few months (spring of 1982) in Baton Rouge. William DeLoach and Mike Cunningham assisted with laboratory analyses. Finally, I wish to acknowledge my wife,
Brenda, for her encouragement, understanding and most of all, patience during the latter months of the ordeal. Financial support for this study provided by Applied Carbonate Research Program at LSU. "Libby" Boihem gave considerable personal time and holidays to type the manuscript.
TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>ii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>ix</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>x</td>
</tr>
<tr>
<td>LIST OF PLATES</td>
<td>xiii</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>xiv</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>Location</td>
<td>3</td>
</tr>
<tr>
<td>Previous Work</td>
<td>6</td>
</tr>
<tr>
<td>Objectives</td>
<td>6</td>
</tr>
<tr>
<td>REGIONAL GEOLOGY</td>
<td>8</td>
</tr>
<tr>
<td>Stratigraphic Nomenclature</td>
<td>8</td>
</tr>
<tr>
<td>Eagle Mills Formation</td>
<td>8</td>
</tr>
<tr>
<td>Louann - Werner Formations</td>
<td>11</td>
</tr>
<tr>
<td>Norphlet Formation</td>
<td>11</td>
</tr>
<tr>
<td>Smackover Formation</td>
<td>12</td>
</tr>
<tr>
<td>Haynesville Formation - Buckner Member</td>
<td>13</td>
</tr>
<tr>
<td>Paleogeography and Structure</td>
<td>16</td>
</tr>
<tr>
<td>GEOLOGY OF JAY - BIG ESCAMBIA CREEK FIELD AREA</td>
<td>22</td>
</tr>
<tr>
<td>Geologic Setting</td>
<td>22</td>
</tr>
<tr>
<td>Well Selection</td>
<td>29</td>
</tr>
<tr>
<td>Lithology and Depositional Environment -</td>
<td>31</td>
</tr>
<tr>
<td>Smackover Formation</td>
<td>31</td>
</tr>
<tr>
<td>Lower Smackover Member</td>
<td>31</td>
</tr>
<tr>
<td>Laminated mudstone facies</td>
<td>31</td>
</tr>
<tr>
<td>Pellet - peloid packstone facies</td>
<td>34</td>
</tr>
<tr>
<td>Section</td>
<td>Page</td>
</tr>
<tr>
<td>------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>Upper Smackover Member</td>
<td>45</td>
</tr>
<tr>
<td>Pellet wackestone facies</td>
<td>48</td>
</tr>
<tr>
<td>Grainstone facies</td>
<td>51</td>
</tr>
<tr>
<td>Pellet packstone - anhydrite sequence (uppermost Smackover - Buckner transitional sequence)</td>
<td>60</td>
</tr>
<tr>
<td>Lithology and Depositional Environment -</td>
<td></td>
</tr>
<tr>
<td>- Buckner Member</td>
<td>66</td>
</tr>
<tr>
<td>Anhydrite and Dolomite</td>
<td>66</td>
</tr>
<tr>
<td>Halite</td>
<td>70</td>
</tr>
<tr>
<td>Depositional History</td>
<td>74</td>
</tr>
<tr>
<td>Lower Member - Smackover Formation</td>
<td>76</td>
</tr>
<tr>
<td>Upper Member - Smackover Formation</td>
<td>77</td>
</tr>
<tr>
<td>Buckner Member</td>
<td>78</td>
</tr>
<tr>
<td>Diagenetic Fabrics</td>
<td>79</td>
</tr>
<tr>
<td>Isopachous Rim Cements</td>
<td>82</td>
</tr>
<tr>
<td>Lower Smackover Member</td>
<td>82</td>
</tr>
<tr>
<td>Upper Smackover Member</td>
<td>82</td>
</tr>
<tr>
<td>Moldic Porosity and Microspar</td>
<td>85</td>
</tr>
<tr>
<td>Lower Smackover Member</td>
<td>85</td>
</tr>
<tr>
<td>Upper Smackover Member</td>
<td>86</td>
</tr>
<tr>
<td>Uppermost Smackover and Buckner</td>
<td>87</td>
</tr>
<tr>
<td>Blocky Calcite Cement</td>
<td>88</td>
</tr>
<tr>
<td>Dolomite</td>
<td>89</td>
</tr>
<tr>
<td>Lower Smackover Member</td>
<td>89</td>
</tr>
<tr>
<td>Upper Smackover Member</td>
<td>90</td>
</tr>
<tr>
<td>Topic</td>
<td>Page</td>
</tr>
<tr>
<td>-------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>Buckner Member</td>
<td>93</td>
</tr>
<tr>
<td>Compaction</td>
<td>93</td>
</tr>
<tr>
<td>Lower Smackover Member</td>
<td>93</td>
</tr>
<tr>
<td>Upper Smackover Member</td>
<td>93</td>
</tr>
<tr>
<td>Saddle Dolomite</td>
<td>94</td>
</tr>
<tr>
<td>Sulfides and Sulfates</td>
<td>95</td>
</tr>
<tr>
<td>Lower Smackover Member</td>
<td>101</td>
</tr>
<tr>
<td>Upper and Uppermost Smackover</td>
<td>101</td>
</tr>
<tr>
<td>Buckner Member</td>
<td>102</td>
</tr>
<tr>
<td>Calcite</td>
<td>106</td>
</tr>
<tr>
<td>Lower Smackover Member</td>
<td>107</td>
</tr>
<tr>
<td>Upper Smackover Member</td>
<td>107</td>
</tr>
<tr>
<td>Buckner Member</td>
<td>108</td>
</tr>
<tr>
<td>Fluorite</td>
<td>110</td>
</tr>
<tr>
<td>Silica</td>
<td>111</td>
</tr>
<tr>
<td>Lower Smackover Member</td>
<td>111</td>
</tr>
<tr>
<td>Upper Smackover Member</td>
<td>111</td>
</tr>
<tr>
<td>Cathodoluminescence</td>
<td>112</td>
</tr>
<tr>
<td>Lower Smackover Member</td>
<td>113</td>
</tr>
<tr>
<td>Upper Smackover Member</td>
<td>113</td>
</tr>
<tr>
<td>Buckner Member</td>
<td>114</td>
</tr>
<tr>
<td>Two-Phase Fluid Inclusions</td>
<td>114</td>
</tr>
<tr>
<td>Chemistry</td>
<td>116</td>
</tr>
<tr>
<td>Presentation of Dolomite Chemistry Data</td>
<td>117</td>
</tr>
<tr>
<td>Dolomite X-Ray Diffraction</td>
<td>130</td>
</tr>
<tr>
<td>Dolomite Cation Concentrations</td>
<td>133</td>
</tr>
</tbody>
</table>

-vi-
<table>
<thead>
<tr>
<th>Topic</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dolomite Stoichiometry</td>
<td>133</td>
</tr>
<tr>
<td>Trace elements - Strontium, Sodium</td>
<td>136</td>
</tr>
<tr>
<td>Oxygen and Carbon Stable Isotope Data</td>
<td>149</td>
</tr>
<tr>
<td>Buckner Dolomite</td>
<td>150</td>
</tr>
<tr>
<td>Lower Smackover Dolomite</td>
<td>162</td>
</tr>
<tr>
<td>Upper Smackover Dolomite</td>
<td>165</td>
</tr>
<tr>
<td>Saddle Dolomite</td>
<td>173</td>
</tr>
<tr>
<td>Radiogenic Strontium</td>
<td>176</td>
</tr>
<tr>
<td>Discussion</td>
<td>184</td>
</tr>
<tr>
<td>Chemical Discontinuity</td>
<td>184</td>
</tr>
<tr>
<td>Exxon Swift - Middle Smackover</td>
<td>205</td>
</tr>
<tr>
<td>Dolomitization</td>
<td>206</td>
</tr>
<tr>
<td>Buckner and Uppermost Smackover</td>
<td>206</td>
</tr>
<tr>
<td>Lower Smackover Dolomite</td>
<td>208</td>
</tr>
<tr>
<td>Upper Smackover Dolomite</td>
<td>214</td>
</tr>
<tr>
<td>Saddle Dolomite</td>
<td>238</td>
</tr>
<tr>
<td>Late Diagenesis</td>
<td>240</td>
</tr>
<tr>
<td>CONCLUSIONS</td>
<td>246</td>
</tr>
<tr>
<td>BIBLIOGRAPHY</td>
<td>251</td>
</tr>
<tr>
<td>APPENDIX</td>
<td>273</td>
</tr>
<tr>
<td>A. Analytical Methods</td>
<td></td>
</tr>
<tr>
<td>Thin Section Staining</td>
<td>274</td>
</tr>
<tr>
<td>Sample Preparation - Anhydrite and Calcite Removal</td>
<td>275</td>
</tr>
<tr>
<td>Atomic Absorption</td>
<td>276</td>
</tr>
<tr>
<td>X-Ray Diffraction</td>
<td>277</td>
</tr>
</tbody>
</table>
Isotopes................................................................. 278
Cathodoluminescence............................................. 279
B. Chemical Data Tables......................................... 280
  Atomic Absorption  B-1, B-2................................. 281
  X-Ray Diffraction  B-3......................................... 285
  Isotopes of Oxygen and Carbon  B-4, B-5................... 287
  Subsurface Brines - Jay area  B-6............................ 289
C. Discussion....................................................... 290
  Sulfur Isotopes  C-1........................................... 291
  Dolomitization model of Powell (1984)..................... 298
D. Abbreviations and Symbols in Stratigraphic Sections
   (PLATES I-VI) D-1, D-2................................. 299
VITA.............................................................. 302
## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Wells studied</td>
<td>30</td>
</tr>
<tr>
<td>2.</td>
<td>Radiometric $^{87}\text{Sr}/^{86}\text{Sr}$ of upper and uppermost Smackover dolomites</td>
<td>180</td>
</tr>
<tr>
<td>3.</td>
<td>Summary of upper Smackover Dolomite Models</td>
<td>237</td>
</tr>
<tr>
<td>B-1</td>
<td>Atomic Absorption Data - Jay area Dolomites</td>
<td>281</td>
</tr>
<tr>
<td>B-2</td>
<td>Atomic Absorption Data - Analysis of Standards</td>
<td>284</td>
</tr>
<tr>
<td>B-3</td>
<td>X-Ray Diffraction Data</td>
<td>285</td>
</tr>
<tr>
<td>B-4</td>
<td>Isotopes of Oxygen and Carbon - Jay area Dolomites</td>
<td>287</td>
</tr>
<tr>
<td>B-5</td>
<td>Isotopes of Oxygen and Carbon - Analysis of Standards</td>
<td>288</td>
</tr>
<tr>
<td>B-6</td>
<td>Subsurface Brines - Jay area</td>
<td>289</td>
</tr>
<tr>
<td>C-1</td>
<td>Isotopes of Sulfur</td>
<td>296</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>1.</td>
<td>Major paleogeographic and structural features of Alabama and Florida</td>
<td>4</td>
</tr>
<tr>
<td>2.</td>
<td>Stratigraphic nomenclature</td>
<td>9</td>
</tr>
<tr>
<td>3.</td>
<td>Type log - Jay Field area</td>
<td>14</td>
</tr>
<tr>
<td>4.</td>
<td>Schematic dip cross section</td>
<td>18</td>
</tr>
<tr>
<td>5.</td>
<td>Top Smackover structure map of the Jay Field area</td>
<td>23</td>
</tr>
<tr>
<td>6.</td>
<td>Cross section showing general stratigraphy of the area</td>
<td>25</td>
</tr>
<tr>
<td>7.</td>
<td>Net thickness of porosity in upper Smackover grainstones</td>
<td>27</td>
</tr>
<tr>
<td>8.</td>
<td>Lower Smackover - photomicrographs of laminated rocks</td>
<td>32</td>
</tr>
<tr>
<td>9.</td>
<td>Lower Smackover - (a) slab photos. of typical pellet-peloid packstones, (b and c) photomicrographs of pellet-peloid packstones</td>
<td>35</td>
</tr>
<tr>
<td>10.</td>
<td>Lower Smackover - photomicrographs of moldic porosity</td>
<td>39</td>
</tr>
<tr>
<td>11.</td>
<td>White, felted crystal anhydrite nodules</td>
<td>41</td>
</tr>
<tr>
<td>12.</td>
<td>Smackover isopach map of Jay - Blackjack Creek area</td>
<td>46</td>
</tr>
<tr>
<td>13.</td>
<td>Upper Smackover - photomicrographs of lime pellet wackestone</td>
<td>49</td>
</tr>
<tr>
<td>14.</td>
<td>Upper Smackover - photomicrographs of grainstone fabrics</td>
<td>53</td>
</tr>
<tr>
<td>15.</td>
<td>Oolite grain size ranges of Jay area compared to south Arkansas and Jolters Cay, Bahamas</td>
<td>56</td>
</tr>
<tr>
<td>16.</td>
<td>Upper Smackover - photomicrograph of grainstones</td>
<td>58</td>
</tr>
<tr>
<td>17.</td>
<td>Uppermost Smackover: (a) photomicrograph of grainstone fabric; (b and c) core slabs of polymictic breccias</td>
<td>62</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>18.</td>
<td>Buckner evaporites: (a and b) slabs of laminated anhydrite and silty claystone with pseudomorphs of halite respectively, (c) photomicrograph of silty anhydrite.</td>
<td>68</td>
</tr>
<tr>
<td>19.</td>
<td>Schematic cross-sections of Jay area with two possibilities for uppermost Smackover correlation.</td>
<td>80</td>
</tr>
<tr>
<td>20.</td>
<td>Upper Smackover - photomicrographs of early isopachous circumgranular cements.</td>
<td>83</td>
</tr>
<tr>
<td>21.</td>
<td>Photomicrograph - soft sediment compaction.</td>
<td>96</td>
</tr>
<tr>
<td>22.</td>
<td>Photomicrograph - soft sediment compaction.</td>
<td>98</td>
</tr>
<tr>
<td>23.</td>
<td>Photomicrographs of upper Smackover evaporites.</td>
<td>104</td>
</tr>
<tr>
<td>24.</td>
<td>Chemistry of Humble #1 Shell 20-1.</td>
<td>118</td>
</tr>
<tr>
<td>25.</td>
<td>Chemistry of Exxon #1 Swift 10-5.</td>
<td>120</td>
</tr>
<tr>
<td>26.</td>
<td>Chemistry of Exxon #15 W. St. Regis.</td>
<td>122</td>
</tr>
<tr>
<td>27.</td>
<td>Chemistry of Exxon #1 McCurdy 12-1.</td>
<td>124</td>
</tr>
<tr>
<td>28.</td>
<td>Chemistry of Exxon #1 Hart 26-3.</td>
<td>126</td>
</tr>
<tr>
<td>29.</td>
<td>Chemistry of Chevron #1 Scott.</td>
<td>128</td>
</tr>
<tr>
<td>30.</td>
<td>Diffractogram trace of typical upper and lower Smackover dolomites.</td>
<td>131</td>
</tr>
<tr>
<td>31.</td>
<td>Cross-plot of Sr versus $^8$O of Smackover and Buckner dolomites compared to other ancient dolomites.</td>
<td>138</td>
</tr>
<tr>
<td>32.</td>
<td>Cross-plot of Sr versus Na for Jay area dolomites compared to other Texas dolomites.</td>
<td>144</td>
</tr>
<tr>
<td>33.</td>
<td>Cross-plot of $^8$O and $^13$C of Jay area dolomites.</td>
<td>151</td>
</tr>
<tr>
<td>34.</td>
<td>Oxygen and carbon stable isotopes of Jay area dolomites supplemented with additional data from recent studies.</td>
<td>153</td>
</tr>
<tr>
<td>35.</td>
<td>Oxygen and carbon stable isotopes of Jay area dolomites compared to Recent dolomites of evaporative origin.</td>
<td>155</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>36.</td>
<td>Oxygen and carbon stable isotopes of Jay area compared to other ancient dolomites</td>
<td>157</td>
</tr>
<tr>
<td>37.</td>
<td>Oxygen and carbon stable isotopes of Jay area compared to south Arkansas and east Texas Smackover and Buckner dolomites</td>
<td>160</td>
</tr>
<tr>
<td>38.</td>
<td>Oxygen and carbon stable isotopes of Jay area compared to dolomites of suspected mixed marine - meteoric water origin</td>
<td>167</td>
</tr>
<tr>
<td>39.</td>
<td>$^{87}\text{Sr}/^{86}\text{Sr}$ seawater temporal variations</td>
<td>177</td>
</tr>
<tr>
<td>40.</td>
<td>Detailed Smackover - Buckner chemistry of Humble #1 Shell 20-1</td>
<td>185</td>
</tr>
<tr>
<td>41.</td>
<td>Detailed Smackover - Buckner chemistry of Exxon #1 Swift 10-5</td>
<td>187</td>
</tr>
<tr>
<td>42.</td>
<td>Detailed Smackover - Buckner chemistry of Exxon #15 W. St. Regis</td>
<td>189</td>
</tr>
<tr>
<td>43.</td>
<td>Detailed Smackover - Buckner chemistry of Humble Moncrief 10-2</td>
<td>192</td>
</tr>
<tr>
<td>44.</td>
<td>Detailed Smackover - Buckner chemistry of Humble Braxton 21-1</td>
<td>194</td>
</tr>
<tr>
<td>45.</td>
<td>Comparison of rock fabric above and below discontinuity</td>
<td>198</td>
</tr>
<tr>
<td>46.</td>
<td>Detailed Lithologic description of Exxon Moore 23-E well in Blackjack Creek Field</td>
<td>200</td>
</tr>
<tr>
<td>47.</td>
<td>Detailed Lithologic description of Humble St. Regis 14-4 well in Blackjack Creek Field</td>
<td>202</td>
</tr>
<tr>
<td>48.</td>
<td>Cross-plot of Ca versus $\text{SO}_4$ activity in seawater</td>
<td>212</td>
</tr>
<tr>
<td>49.</td>
<td>Mg/Ca versus salinity</td>
<td>229</td>
</tr>
<tr>
<td>50.</td>
<td>Model of two mechanisms for fluxing seawater or evaporated seawater through the shoal grainstones</td>
<td>232</td>
</tr>
<tr>
<td>51.</td>
<td>Paragenetic sequence for Jay-Big Escambia Creek area</td>
<td>241</td>
</tr>
<tr>
<td>52.</td>
<td>Marine sulphur $^{32}\text{S}/^{34}\text{S}$ temporal variations</td>
<td>292</td>
</tr>
</tbody>
</table>
LIST OF PLATES

PLATE

I. Lithologic Log of Chevron #1 Scott
II. Lithologic Log of Exxon #1 McCurdy 12-1
III. Lithologic Log of Exxon #1 Hart 26-3
IV. Lithologic Log of Humble #1 Shell 20-1
V. Lithologic Log of Exxon #1 Swift 10-5
VI. Lithologic Log of Exxon #15 W. St. Regis
VII. Structural Map Top Smackover Formation
VIII. Isopach Map Smackover Formation
IX. Isopach Map Buckner Member, Haynesville Formation
X. Isopach Map Haynesville salt-stringer interval
XI. Isopach Map Net Porosity, Smackover Formation
XII. Stratigraphic cross-section B-B'
XIII. Stratigraphic cross-section C-C'
XIV. Stratigraphic cross-section D-D'
XV. Stratigraphic cross-section E-E'
XIV. Stratigraphic cross-section of upper Smackover - Buckner interval across Jay Field in east-west orientation (from Powell, 1984)
ABSTRACT

The Smackover-Buckner sequence in the Jay-Big Escambia Creek area has three major lithostratigraphic units: lower Smackover, upper Smackover, and Buckner with an uppermost Smackover transitional sequence. The lower Smackover is regionally extensive, mostly low energy subtidal to intertidal, dolomitized packstones with abundant displacive anhydrite nodules. The upper Smackover is characterized by thick oolite-peloid high energy grainstone buildups generated over Louann salt induced bathymetric highs which were surrounded by areas of low energy, subtidal mudstones-wackestones. The Buckner is mostly nodular mosaic anhydrite with minor amounts of dolomite mudstones-packstones. Below the Smackover-Buckner contact in the grainstone areas is a transitional sequence (referred to here as uppermost Smackover) of high intertidal-low supratidal dolomitized mudstones-grainstones interbedded with nodular mosaic anhydrite layers.

A combination of stratigraphic and geochemical evidence indicate dolomites of four separate origins, three of which are early diagenetic. The dolomites of the Buckner-uppermost Smackover have supratidal stratigraphy, heavy oxygen isotopic composition (mean $^{18}O = +1.5\%$ PDB), high trace element composition (average Sr=202 ppm, Na=320 ppm) and are syndepositional. Immediately below and separated by a sharp chemical discontinuity within porous and permeable rock, are the upper Smackover oomoldic grainstone dolomites which are coarsely crystalline, well ordered, stoichiometric dolomites lower in $^{18}O$ composition (average $= -2.0\%$ PDB) and lower in trace element composition (average Sr = 73 ppm, Na = 228 ppm). Further delineation
of the discontinuity by Powell (1984) shows definite flatness or horizontality across Jay Field. Combined with evidence of subaerial exposure (breccias) the chemical discontinuity is believed to be the remnants of a paleo-water table which existed in an island complex prior to uppermost Smackover and Buckner deposition. Moldic porosity development and subsequent dolomitization of the upper Smackover dolomite probably occurred in a mixed evaporated marine-meteoric water system (schizohaline) which existed during the subaerial exposure event.
INTRODUCTION

In order to determine the origin of ancient dolomites it has become common practice to compare their geochemistry to that of analogous Holocene dolomitic sediments. In many studies the stratigraphic comparisons are dissimilar to some extent, but this uniformitarianistic approach is all that can be done considering the present state of knowledge. There is an advantage, however, if within an ancient stratigraphic sequence a dolomite of known origin exists with its original chemistry preserved. The dolomite can then be used as an "internal standard". Such is the case with the Smackover-Buckner sequence in the Jay Field area. In this study, Smackover dolomites are compared to Buckner dolomites which are encased in impermeable anhydrite. Therefore, they stand the best chance of having avoided re-equilibration, and consequently are used as an internal standard.

Another common problem is that doubts are cast upon the geochemistry of ancient dolomites which occur in outcrop. What are the effects, if any, of exposure to present day, Tertiary or Mesozoic meteoric waters? The Jay area Smackover has a simple tectonic history of progressive burial with no major unconformities in the overlying Mesozoic and Cenozoic section. This burial history combined with the sealing effect of the regionally continuous Buckner anhydrite and the discontinuous nature of lateral Smackover porosity distribution, minimize the chances of water coming from above or updip which would change Smackover water chemistry and cause rock-water reequilibration. Therefore, waters used to explain the formation of the Smackover dolomites in question must come from below.
or be more or less contemporaneous with the Jurassic stratigraphic sequence.

For this study wells were selected where continuous core was taken through the entire Smackover and lower Buckner sequence. A total of 103 dolomite samples from the lower Smackover (40 samples from 5 wells), upper Smackover (56 samples from 3 wells) and Buckner (7 samples from 3 wells) were analyzed for Sr**, Na*, Mg** and Ca** cation concentrations by atomic absorption spectroscopy. The magnesium-calcium ratios were double checked by X-ray diffraction (XRD) techniques (after Katz, 1971). Seventy samples were analyzed for the oxygen and carbon stable isotopes (procedural details are discussed in appendices). The new geochemical evidence helps define the various dolomite types and their origins.

The origin of dolomite has been a problem for decades. In the 60's the question was whether the crystals were primary precipitates from aqueous solution or host rock replacement products (Friedman and Sanders, 1967). Controversy surrounding dolomite today concerns the composition of the waters responsible for dolomitization and timing of the dolomitization (early diagenetic versus deep burial) or whether the dolomite has been recrystallized. Were the dolomitizing fluids hyper- or hyposaline in an open or closed hydrologic setting?

Since Jay Field was discovered in 1970, geologists have speculated whether the Smackover was dolomitized by brackish waters over paleostructural highs or by reflux of hypersaline Buckner brines from above. Based only on stratigraphy, the brine reflux interpretation is favored by Ottman and others (1973), Sigsby (1976),
Wagner (1978) and Koepnick and others (1985). Feazel (1980), Vinet (1982, 1984) and Mitchell-Tapping (1988) favored the fresh-seawater mixing mechanism. Another possibility is that dolomitization was syndepositional. If the Smackover oolites accumulated in restricted seas with salinities periodically 2 or 3 times seawater, minor calcium sulfate precipitation and oolite accretion at elevated temperatures may raise the Mg/Ca sufficiently to precipitate dolomite (Friedman, 1980). Based mainly on carbon isotopic analysis, normal salinity seawater also has been proposed as a mechanism for upper Smackover dolomitization (Sailer and Moore, 1984). A fourth possibility is that of moderate to deep burial dolomitization. Smackover subsurface brines are similar in composition to evaporated seawater brines modified by dolomitization and sulfate precipitation (Carpenter, 1980; Carpenter and Trout, 1978). If compaction and dewatering of the Louann salt produced brines which displaced Smackover connate water, then the dolomitization of the upper Smackover sequence at Jay could have lowered the Mg/Ca to presently observed levels. All of these ideas are examined in the following text.

Location

The area of concern in this study lies in and around Jay and Big Escambia Creek Fields. These Smackover fields are near the Alabama-Florida state line approximately 30-40 miles north of Pensacola, Florida (Figure 1). Other important nearby fields are Flomaton, which is situated between Big Escambia Creek and Jay, and Blackjack Creek which lies southeast of Jay Field. Big Escambia Creek, Jay and Blackjack Creek Fields produce oil and sour gas
Figure 1.

Major paleogeographic and structural features of southern Alabama and western Florida with approximate updip limits of the Smackover and Louann (modified from Ottman and others, 1973).
condensate from porous Smackover dolomites and Norphlet sands.

Flomaton Field produces sour gas from the Norphlet sands.

Previous Work

Previous studies of the Jay Field area were devoted almost entirely to establishing the Norphlet-Smackover-Buckner depositional environments (Ottman and others, 1973; Sigsby, 1976; Lomando, 1979; Powell, 1984; Bradford, 1984; Koepnick and others, 1985; Lloyd and others, 1986; Mitchell-Tapping, 1988). Ottman and others (1973) and Sigsby (1976) briefly mentioned some early diagenetic effects, whereas Wagner (1978) and Feazel (1980) constructed complete paragenetic sequences based on petrographic relationships. Wagner (1978) and Mitchell-Tapping (1988) studied the petrography and stratigraphy of a producing structure (Blackjack Creek Field) and Feazel (1980) did a regional study utilizing wildcat and field wells in southern Mississippi, Alabama and Florida. Leiker (1977) and Barrett (1986) attempted to characterize the dolomite of the Vocation Field area north of Big Escambia Creek Field and Leiker (1977) claimed he could recognize a sedimentary facies by its trace element composition. Other recent contributions to stratigraphy mostly to the west and north, are provided by Oxley (1967), Badon (1973), Wilson (1975), Wakelyn (1977), Mancini (1980), Benson and Mancini (1982), Benson (1984), Moore (1984), Benson (1985), Prather (1986), Saller and Moore (1986), Lowenstein (1987), Meendsen and others (1987) and Mann (1988).

Objectives

The purpose of this study is to determine the origin(s) of the Smackover dolomite(s) by supplementing the stratigraphy and
petrography with trace element and stable isotope geochemistry. The Smackover in the Jay Field area makes an ideal stratigraphic test case for a number of reasons: a) the stratigraphic framework of the area is well established, b) conventional core is available of the continuous Norphlet-Smackover-Buckner vertical sequences, c) core is available from wells on and off structure, d) the chemistry of dolomite layers (Buckner) encased within impermeable anhydrite can be used as an "internal standard" for comparative purposes, e) the Jay area Smackover has a simple tectonic history of progressive burial with no major unconformities in the overlying Mesozoic and Cenozoic section. The minor tectonism and the sealing effect of the regionally continuous Buckner anhydrite minimize the chances of water coming from above which would change Smackover water chemistry and cause rock-water reequilibration. Therefore, the only waters available for Smackover diagenesis are Smackover connate waters and upward migrating waters due to compaction of underlying strata. There is speculation on the effects of Buckner waters possibly generated from gypsum to anhydrite inversion (Bradford, 1984) but few studies are available to support dolomitization by such a process.
REGIONAL GEOLOGY

Stratigraphic Nomenclature

The formational nomenclature used in this study follows the usage of Hazzard and others (1947) for the Norphlet Formation, and of Weeks (1938) for the Smackover and Buckner Formations of southern Arkansas (Figure 2). As new discoveries extended the Smackover trend eastward during the 50s, 60s and 70s, this formational terminology was adopted due to consistency in the Jurassic vertical sequence. Current usage (Badon, 1973; Ottman and others, 1973; Sigsby, 1976; Wakeland, 1977; Leiker, 1977; Wagner, 1978; Mancini and Benson, 1980; Meendsen and others, 1987; Wade and others, 1987; and so on) is without controversy. Eagle Mills, Werner and Louann Formations are included in the introductory text for completeness.

Eagle Mills Formation

The Eagle Mills Formation was named from a 1929 Amerada Petroleum Company well drilled in Ouachita County, Arkansas. It consists of red-grey, terrigenous clays, silts, sands and conglomerates of continental origin (Scott and others, 1961). Shallow intrusives of diabase composition are associated with Eagle Mills sediments similar to the equivalent Newark Series of the Atlantic Coastal Plain. The Eagle Mills accumulated in grabens formed during Late Triassic (plant imprints based on the interpretation by Scott and others in 1961) taphrogenesis. The Eagle Mills lies unconformably on Paleozoic rocks and is overlain unconformably by the Werner Formation. Very few wells in the Northern Gulf Coast penetrate the Eagle Mills.
Figure 2.

Stratigraphic nomenclature modified from Meendsen and others (1987); sea level curve from Todd and Mitchum (1977).
<table>
<thead>
<tr>
<th>FORMATION</th>
<th>MEMBER</th>
<th>RELATIVE CHANGES IN SEA LEVEL</th>
<th>STAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>CENTRAL/WESTERN GULF</td>
<td>CENTRAL/WESTERN GULF</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EASTERN GULF</td>
<td>EASTERN GULF</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SCHULER (COTTON VALLEY GROUP)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BOSSIER</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HAYNESVILLE</td>
<td>GILMER LIMESTONE</td>
<td></td>
<td>TITHONIAN</td>
</tr>
<tr>
<td></td>
<td>UPPER BUCKNER</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>BUCKNER EVAPORITE</td>
<td>LOWER HAYNESVILLE</td>
<td></td>
</tr>
<tr>
<td>SMACKOVER</td>
<td>UPPER SMACKOVER</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>MIDDLE SMACKOVER</td>
<td>LOWER SMACKOVER</td>
<td>OXFORDIAN</td>
</tr>
<tr>
<td>NORPHLET</td>
<td></td>
<td>DENKMAN</td>
<td></td>
</tr>
<tr>
<td>LOUANN</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WERNER</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EAGLE MILLS</td>
<td></td>
<td>PALEOZOIC BASEMENT</td>
<td></td>
</tr>
</tbody>
</table>
Louann-Werner Formations

The Louann salt and Werner Formation were named by Hazzard and others, (1947) from the Gulf No. 49 Werner Saw Mill, Sec. 5, T16S, R16W, Union County, Arkansas. Louann salt conformably overlies Werner anhydrite where both are present. The anhydrite extends farther updip than the salt and they may in part be laterally equivalent. The exact age of the salt is unknown, though Middle-Late Jurassic palynomorphs from caprock on the Challenger Knoll in the Gulf of Mexico were reported by Kirkland and Gerhard (1971). In the Jay Field area the Louann salt has a maximum thickness of approximately 1500 feet (Sigsby 1976).

Norphlet Formation

The Norphlet Formation was defined by Hazzard and others, (1947) as red and gray shales interbedded with red and gray sandstones. The type locality is the same as for the Louann and Werner Formations referenced above. In Mississippi, Badon (1973) was able to subdivide the Norphlet into two members and five subfacies. In the Jay Field area, Sigsby (1976) described a lower unit of desiccated mudstones and anhydrite probably equivalent to Badon's supratidal red siltstone lower member. These lower Norphlet tidal flat sediments may be stratigraphic equivalents to the uppermost Louann salt (Sigsby, 1976). The upper Norphlet members in both areas are dominated by sandy facies with conglomeratic channel deposits more common in Florida. Tyrrell (1972) suggested that the uppermost white sandstone was fluvial to eolian in origin but Badon (1973) and Sigsby (1976) prefered an intertidal interpretation in their respective areas. The discovery of Mary Ann Field (1979) in Lower
Mobile Bay, Alabama sparked new interest in the Norphlet. The resulting flurry of papers in the 1980s describe an arid basin fluvial-eolian depositional system composed of dune, interdune and evaporite sediments (Mancini and others, 1984; Mancini and others, 1985; Marzano and others, 1988; Pense, 1988). The reworked sands in the upper Norphlet provide the best reservoir rocks usually due to secondary porosity enhancement (Thomson and others, 1987; Vaughn and Benson 1988; Pense, 1988; Dixon and others, 1989).

Smackover Formation

The Smackover Formation was originally defined by Weeks (1938) as a lower cryptocrystalline limestone overlain by soft, chalky, limestone and oolitic limestone in Union County, Arkansas. The electric log character of the Smackover-Norphlet contact is typically sharp though it may occasionally be gradational (Sigsby, 1976).

The Smackover was originally divided into three members in south Arkansas (Dickinson, 1968). Basically, however, it has two units in Mississippi, Alabama, and Florida. The lower member, often called the "brown dense", is dark laminated argillaceous lime mudstones-wackestones. The upper member is composed of low energy carbonate mudstones as well as higher energy grainstones with abundant oolites, rhodolites, and oncolites. The gross lithology is limestone to dolomite with varying amounts of terrigenous quartz. The lower member is considered to have accumulated in deeper water during the initial Smackover transgression (Bishop, 1968) with the upper member deposited in shallower water during a regressive phase.
Considerable stratigraphic analyses in recent years (Mancini and Benson, 1980; Benson, 1985) as well as others (Leiker, 1977; Bradford, 1984; Sailer and Moore, 1986; Barrett, 1986; Ottman and others, 1973; Sigsby, 1976) revealed the basic complexity of shallow marine to tidal flat Smackover environments. In Mississippi, Arkansas and Texas, the Smackover was commonly divided into three members (Dickinson, 1968; Bishop, 1968; Badon, 1973, Moore, 1984, Meendsen and others, 1987). However, in southern Alabama - northwestern Florida the Smackover is thinner (usually less than 500 feet thick), more dolomitic, less terrigenous and generally divisible into two units, upper and lower (Figure 3).

Haynesville Formation - Buckner Member

Weeks (1938) proposed the Buckner Formation for strata overlying the Smackover Formation in Union County, Arkansas. In the type well, the Buckner consists of an upper unit of red shale, a middle unit of red shale with nodules of anhydrite, and a basal unit consisting mainly of anhydrite with some stringers of red shale and dolomite. These units were later included in the Haynesville Formation and the term "Buckner" was retained for the basal massive anhydrite (Phillpaott and Hazzard, 1949).

In the eastern portion of the Gulf rim, the stratigraphic usage of the Buckner anhydrite has been inconsistent with some authors using it as a formation (Badon, 1974; Lomando, 1979; Bradford, 1984; Lowenstam, 1987), member (Oxley and others, 1967, Leiker, 1977; Tolson and others, 1983; Moore, 1984; Barrett, 1986; Mann, 1988) or not at all in favor of Lower Haynesville (Meendsen and others, 1987). The writer is in support of Moore (1984) who
Figure 3.

Type log - Jay Field area, LL&E No. 1 Miller Mill 35-3, Sec. 35, T6N-R30W, Escambia County, Florida. The log to the left is a density - Neutron log. To the right is the Dual Induction Laterolog with S.P. curve. In this particular well, the Haynesville Formation is 920 feet thick with 30 feet of Buckner anhydrite at its base. A 110 foot thick interval of salt stringers overlie the Buckner. The Smackover is 360 feet thick with 65 feet of underlying porous Norphlet sands. The well reached total depth in Louann Salt. The highest resistivities in the Haynesville are anhydrite beds. The upper Haynesville anhydrite is a good regional marker throughout the area. The salt interval typically washes out and produces low resistivities on the induction log.
La. Land & Expl.
No. 1 Miller Mill Un. 35-3
Section 35, T 6 N - R 30 W
Escambia County, Florida

Resistivity curve

Anhydrite

Red sandstone, shale and anhydrite

Regionally continuous anhydrite bed

Salt stringer interval

BUCKNER MEMBER

Dolomite

Limestone

Dolomite and limestone

Sandstone

Salt

NORPHLET

LOUANN
preferred the status of member to emphasize its subordinate but significant role as a regionally continuous basal Haynesville unit, as well as to encourage standardization of future usage.

The Haynesville Formation in southern Alabama and western Florida (approximately 1000 feet thick in the Jay area) is mostly red, grey-green silts and shales, pink to white sands with interbedded anhydrite stringers (Mann, 1988). Salt stringers which locally become massive are in the lower third of the Haynesville section (Figure 3) immediately above the basal Buckner (member) anhydrite (maximum thickness in the area is 85 feet). Toward Mississippi from the Jay area the Haynesville Formation becomes thicker with more carbonates and less terrigenous sediments. The Smackover-Buckner contact is generally placed at the base of the massive Buckner anhydrite. The contact is usually sharp and will be discussed in considerable detail later in the text. The Haynesville evaporites extend farther updip than do the underlying Smackover and Louann-Werner marine units.

**Paleogeography and Structure**

The terminology used in Figure 1 for major physiographic and structural features of Southern Alabama - Western Florida is that in general use by industry since the late sixties. The eastern updip limit of the Smackover forms a series of embayments due to the southwestward plunging Paleozoic Appalachian ridge and valley structural trend which is onlapped by Mesozoic marine sediments. Major erosional valleys in the Appalachian Paleozoics are sites of Smackover embayments. From Choctaw County, Alabama southeastward, these are called the Manila Basin (Mancini, 1980), Conecuh Basin
(Sigsby, 1976; Mancini, 1980) and Apalachicola Embayments. The Conecuh and Pensacola Ridges are the intervening positive elements. The Wiggins Arch, believed to be an extension of the Conecuh Ridge by Wilson (1975) and Mancini (1980) is an east-west oriented basement high which occupies Hancock, Harrison and Jackson Counties, Mississippi and southern Mobile County, Alabama. Its orientation suggests an origin perhaps more related to Triassic taphrogenesis than Appalachian tectonics.

The updip limit of thick Louann salt forms an approximate boundary between two Smackover structural provinces. In areas underlain by thin or no salt the majority of structures are erosionally resistant Paleozoic highs or monadnocks similar to granite islands behind the Great Barrier Reef, eastern Australia (Maxwell, 1968). Smackover strata may not exist over the crest of monadnocks depending upon the proximity to the Smackover strandline and/or the degree of local basement relief relative to the Jurassic sealevel (Figure 4) (Leiker, 1977; Green, 1985). All of the Jurassic formations thicken away from basement highs as a result of onlapping deposition and/or in response to differential compaction. Examples of these relationships are demonstrated by Leiker (1977) in the Vocation Field area.

Prior to 1979, Smackover production from the updip - basement province was minor. Approximately 10 miles north of Big Escambia Creek Field, 3 fields, Uriah, Vocation and Barnett produce from 1, 4 and 4 wells respectively. Since 1980, additional development wells in Barnett and Vocation Fields and new discoveries at Lovettes Creek, Huxford and Appleton Fields attests to renewed
Figure 4.

Schematic dip cross-section A (southwest) to B (northeast; see Figure 1 for location) with gross stratigraphic relationships in the two major structural provinces. The Pickens to Pollard fault system roughly separates the two provinces.
industry interest in the province. (Green, 1985; Barrett, 1986; Saller and Moore, 1986; Esposito and King, 1987).

The downdip structural province is characterized by salt tectonics which creates large anticlinal structures and regional fault systems. Structures for Blackjack Creek, Jay, Flomaton, and Big Escambia Creek Fields are formed by low relief salt pillows (Hughes, 1968; Moore, 1984), which typify this province. Down-to-the-basin faults and grabens formed immediately updip of the salt pillows. The major fault is called the Pickens-Quitman-Gilbertown-Pollard (Pickens to Pollard) fault system and extends from Santa Rosa County, Florida to Holmes County, Mississippi. The fault bifurcates and may terminate over the axes of the Pensacola and Conecuh ridges as a result of thin or absent Louann salt. Sigsby (1976) presented a detailed discussion of the history of the salt-induced Pickens-Pollard fault movement as it relates to structural evolution and stratigraphy in the Jay area. A comprehensive regional synthesis by Moore (1984) shows the Haynesville-Smackover stratigraphic relationships from the Florida panhandle through Alabama, Mississippi, south Arkansas to east Texas. He provides examples for the various types of hydrocarbon trapping mechanisms and includes field examples of each. East Texas Smackover is well studied (Dickinson, 1968; Loucks and Budd, 1981; Moore and Druckman, 1981; Stamatedes, 1982; Harwood and Fontana, 1984; McGillis, 1984; Stewart, 1984; Wilkinson, 1984; Moore and others, 1988), but far removed from the Jay study area. Therefore, few comparisons between the areas are made here except with regard to the question of dolomitization and diagenesis (Dolomitization section, p.
While the two areas share remarkable similarities in diagenetic fabrics and dolomite chemical composition they differ considerably in paleogeography and stratigraphy (Moore, 1984; Moore and others, 1988).
GEOLOGY OF THE JAY-BIG ESCAMBIA CREEK AREA

Geologic Setting

The present structural trend of the Jay-Big Escambia Creek study area is characterized by a series of low relief salt pillows (Hughes, 1968) which are bounded updip by an arcuate northwest-southeast oriented graben system (Figure 5). Norphlet production (Flomaton Field) is generally structurally controlled due to the regional lateral continuity of porosity in the area. The trapping mechanism in the Smackover, however, may be purely structural (Blackjack Creek Field) or a combination of structure and stratigraphy (Big Escambia Creek and Jay Fields). The combination nature of the Smackover traps is a direct result of primary sedimentation patterns which were controlled by paleo highs and lows (see Depositional History, p. 42). The bathymetric relief was caused by subtle Louann salt movement particularly during upper Smackover and lower Haynesville deposition.

The Smackover Formation throughout the study area varies in thickness from 270 feet to 360 feet. It is divided in this study into an upper and lower member, each of which contains several lithofacies (Figure 6). The 100-150 foot thick lower member is composed mainly of pellet packstones with abundant bioclasts and anhydrite nodules. It is typically dolomitized with the original sediment fabric preserved. The very base of the Smackover may contain a laminated lime mudstone (6 feet thick in Humble #1 Shell, Plate IV) of questionable origin. The upper Smackover member is composed of two distinct lithofacies; a lime mudstone to wackestone facies and a dolomitized grainstone lithofacies (Figure 7). The
Figure 5.

Structure map top Smackover of Jay area (modified after Ottman and others, 1973; and Sigsby, 1976). Wells 1-5 mark location of cross section A-A' in Figure 6. The detailed chemical analyses in this report are exclusively from Wells 1-5 and the Exxon #15 W. St. Regis well marked by the dry-hole symbol south of Blackjack Creek Field. See Plate VII for a more detailed structural map.
Figure 6.

Cross section showing general stratigraphy of the area. The lower Smackover is mostly dolomite. The upper Smackover grainstones are nearly completely dolomitized. See Figure 5. for locations. The four lithologic patterns also apply to lithologic columns in Figures 40-42.
Figure 7.

Net thickness of porosity higher than 10% in upper Smackover grainstones, which pinch out updp into mud supported rocks. Present day regional Smackover dip is approximately 125 feet per mile southwestward. This map is presented in greater detail as Plate XI. Porosity determinations are based on sonic and FDC-CNL logs.
stratigraphic sequence at Jay Field as presented by Ottman and others (1973) illustrates the general stratigraphic lithofacies. With the exception of a few minor differences the writer is in agreement with the stratigraphic framework presented by Ottman and others (1973) and Sigsby (1976).

The Big Escambia Creek portion of this study is based upon 891 feet of core from four wells. Stratigraphic variations within the field are described with greater lithofacies detail in Bradford's (1984) study (4000 feet of core from 20 wells).

Well Selection

The basic Smackover-Buckner stratigraphic relationships in the Jay-Big Escambia Creek area were established by Exxon geologists in the early seventies (Ottman and others, 1973; Sigsby, 1976). This stratigraphic framework was used as a guide to select a producing well with abundant dolomite in order to establish the petrographic variation in a complete vertical sequence of the Smackover and lower Haynesville Formations. Four other wells were then selected, two producing, and two non-producing, to determine the lateral extent of dolomite types (Figures 5 and 6). Wells were sought which could provide continuous core of the Smackover section and the Smackover-Buckner transition. Sample cuttings were not used because of the availability of conventional core and because large samples were necessary for the second phase of the study which was to determine the chemical characteristics of the petrographically determined dolomite types. Table 1 is a list of the wells utilized in this report (see Plate VII for well locations). For convenience, the well names are abbreviated in the text as described in Table 1.
### Table 1. Wells Studied

**Escambia County, Alabama**

<table>
<thead>
<tr>
<th>Operator</th>
<th>Lease</th>
<th>Location</th>
<th>Cored Interval</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chevron</td>
<td>#1 Scott Paper Co., et al</td>
<td>Sec. 29, 2N-6E</td>
<td>15536-878</td>
<td>Chevron Scott</td>
</tr>
<tr>
<td>Exxon</td>
<td>#1 O.M. McGurdy 12-1</td>
<td>Sec. 12, 1N-7E</td>
<td>15254-606</td>
<td>Exxon McGurdy</td>
</tr>
<tr>
<td>Exxon</td>
<td>#1 G.W. Hart 26-3</td>
<td>Sec. 26, 1N-8E</td>
<td>15395-705</td>
<td>Exxon Hart</td>
</tr>
<tr>
<td>Exxon*</td>
<td>#1 Scott Paper Co. 25-1</td>
<td>Sec. 25, 1N-7E</td>
<td>15487-575</td>
<td>Exxon Scott</td>
</tr>
</tbody>
</table>

**Santa Rosa, Florida**

<table>
<thead>
<tr>
<th>Operator</th>
<th>Lease</th>
<th>Location</th>
<th>Cored Interval</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Humble</td>
<td>#1 J.F. Shell 20-1</td>
<td>Sec. 20, 5N-29W</td>
<td>15544-992</td>
<td>Humble Shell</td>
</tr>
<tr>
<td>Exxon</td>
<td>#1 J.B. Swift 10-5</td>
<td>Sec. 10, 5N-29W</td>
<td>15410-724</td>
<td>Exxon Swift</td>
</tr>
<tr>
<td>Exxon</td>
<td>#15 W. St. Regis Paper Co.</td>
<td>Sec. 23, 5N-26W</td>
<td>15980-16063</td>
<td>Exxon St. Regis</td>
</tr>
<tr>
<td>Pennzoil*</td>
<td>#1 St. Forest 5-2</td>
<td>Sec. 5, 3N-26W</td>
<td>15245-440</td>
<td>Pennzoil St. Forest</td>
</tr>
<tr>
<td>Belco*</td>
<td>#1 S.W. Mitchum 23-4</td>
<td>Sec. 23, 2N-28W</td>
<td>16788-877</td>
<td>Belco Mitchum</td>
</tr>
<tr>
<td>Pennzoil*</td>
<td>#1 Cooley 25-1</td>
<td>Sec. 25, 4N-27W</td>
<td>15173-231</td>
<td>Pennzoil Cooley</td>
</tr>
</tbody>
</table>

* Lend petrographic support only, no chemistry.
Lithology and Depositional Environments - Smackover Formation

The emphasis of this report is on the origin of the dolomites in Jay and Big Escambia Creek Fields as inferred from their stratigraphic, petrographic and chemical character. The first step is the determination of the number of dolomite types petrographically as they relate to the stratigraphy. The following descriptions are based on 2,173 feet of logged core and 310 impregnated and stained thin sections. The carbonate lithologic descriptions are according to the classification of Dunham (1962).

**Lower Smackover Member**

Laminated dolomitic mudstone facies: This facies occurs at the base of the Smackover and is observed in three wells; the Exxon McCurdy, the Exxon Hart and the Humble Shell (Figure 6 and Plates II, III and IV), with thicknesses of one, three, and six feet respectively. It consists entirely of laminated finely crystalline dolomite. Laminae in Figure 8 a and b are approximately 0.1 to 0.5 mm. thick with abundant microstylolities. Where microstylololites are not present, laminae are separated by thin, darker-colored zones of dolomite with finely disseminated, microcrystalline pyrite and carbonaceous material. Allochems are very scarce but consist of an occasional detrital quartz or mica grain, pellet, ostracod or thin shelled mollusc. The dolomite crystals at the base of individual laminae are often finely crystalline (a few microns) coarsening upward to 40 or 50 microns.

Although of minor volumetric importance, this facies is distinctive in the Jay area, and is believed to be analogous to
Figure 8.

Lower Smackover
a. Laminated finely crystalline dolomite mudstone. (EMc 15581).
b. Laminations are true depositional layers, probably algal generated. Laminations may be modified by compaction (microstylolites). (EMc 15581)
c. Microstylolites bend around bioclasts indicating soft sediment compaction.
Mississippi (Badon, 1973) and Arkansas (Handford, personal communication) Smackover equivalents. Badon (1973) concluded that subtidal gravity settling best explains such laminated sediment, especially when evidence is lacking for an alternative supratidal algal mat origin. In the Jay area, no new evidence was found which could help define the environment of deposition. However, blue-green algal mats (\textit{microcoleus}) produce strikingly similar laminated sediment in hypersaline or intermittently exposed marine settings (Horodyski and others, 1977).

\textbf{Pellet-peloid packstone facies:} The pellet packstone facies is the most areally extensive of all Smackover facies. It is present in all five wells examined and is, by far, the dominant lithology of the lower Smackover member. The thickness varies from 110 to 140 feet (see Plates I-V). The subtle thickness variations and lithologic homogeneity from well to well suggests prolonged stable depositional conditions with very low seabottom relief at this time over the entire Big Escambia Creek-Jay area.

The facies consists of dark brown (limestone) to medium grey (dolomite) pellet, peloid packstone (Figure 9 b and c) with wackestones occurring near the upper and lower boundaries. Although bioclasts seldom exceed ten percent of the rock, the most common types are echinoid plates, echinoid spines, benthonic foraminifera, ostracodes, and fragments of brachiopods and molluscs. Encrusting bryozoans and segmented or "chambered" algae (similar to \textit{Renalcis}, a Paleozoic blue-green algae found in reef environments, Pratt, 1984) are found in lesser amounts. Other common constituent include peloids, small pellets (0.15 mm) and larger (0.2 to 0.6 mm)
Figure 9.

Pellet-peloid packstone facies-lower Smackover

a. Core slab of typical dolomite packstone with white anhydrite nodules. The dark areas are rich in pyrite.

b, c. Typical sediment fabric of the majority of the lower Smackover dolomite. Note assortment of peloids and multichambered benthonic foraminifera. Both photomicrographs are the same scale.
Favreina sp. pellets, oncolites and intraclasts. Most oncolites seem to be of the spongy type as described by Logan and others (1964) and Badon (1973). Distinction of pellets from peloids is based upon size (pellets ≤ 0.15 mm) except for Favreina sp.

Primary bedding features are scare throughout the pellet packstone facies. Whispy laminations appear to be primarily due to microstylololite swarms (Figure 8 c) also called horsetail structure (Wanless, 1979). The bulk of this facies is mottled gray and massive with few recognizable burrows or sedimentary structures. The abundance of fossils and the ubiquitous grain supported, homogenized nature of the rock suggests intense bioturbation.

Most of the packstones are dolomitized with the bulk of the crystals ranging from 1 to 10 μm. The aphanocrystalline texture (finely crystalline nature of the dolomite) preserves the original sedimentary fabric (Figure 9 b and c). Epitaxial overgrowths on echinoid fragments and the ultrastructure of brachiopod fragments are preserved as dolomite. The majority of this facies consists of 100% dolomite, although many intervals show incomplete dolomitization. With the exception of the Exxon Swift well, 10 to 40% of the facies is limestone or dolomitic limestone. Within the dolomitic limestone, pellets and burrow infills are selectively dolomitized. In addition to replacement dolomite, void fill dolomite cement is present which is discussed in the section on diagenetic fabrics.

The pellet packstone facies generally has low porosity and permeability. There is, however, some porosity present (6-8%) in all five wells examined. In every case the increased porosity is due to selective dissolution of pellets and molluscs which suggests that
they may have originally been aragonitic. The moldic porosity as illustrated in Figure 10 is best developed in the Exxon McCurdy. In hand specimen, the color is a lighter gray and the texture is more chalky as porosity increases. In thin section, allochem boundaries are less distinct than in the nonporous intervals, although there is no significant change in dolomite crystal size. Rounded lithoclasts with moldic porosity are abundant in the nonporous sediments adjacent to porous intervals. The occurrence of pore filling calcite, anhydrite and saddle dolomite increases with porosity.

Anhydrite is abundant in two forms; white, felted crystal nodules up to 3 cm in diameter, and poikilotopic crystals of various sizes (0.5 - 5 mm). The white nodules are polycrystalline aggregates of randomly oriented, felted crystal needles or laths. Some idea of the abundance of nodules is seen in Figure 9a. In the context of a small core it is impossible to know whether the nodules are concentrated along bedding planes or randomly scattered. Sedimentary layers shown in Figure 11a are displaced around nodules indicating physical displacement of sediment as the nodules grew (Schmidt, 1965; Shearman, 1973). Nodules are observed to coalesce forming localized nodular mosaic or "chicken wire" patterns (Figure 11b). Another common feature associated with the nodules is a digitate, bouquet-like pattern which extends upward from the nodule (Figure 11c). The associated nodule appears to be reduced in size. Finely disseminated pyrite highlights the digitate pattern. Both features obviously formed while the sediment was soft, which supports an early origin for the nodules.
Figure 10.

Dissolution of peloids has produced moldic porosity, a distinctly chalky texture in core and hand sample and seems to be responsible for increased permeability. Also note the coarser crystal size. (EMc. - 15558).
Figure 11.

White felted crystal anhydrite nodules are displacive (a.), coalescing (b.) and sometimes reduced from their original size (c). Photo (a) shows soft sediments were displaced as the nodule grew. Photo (b.) shows how multiple anhydrite nucleation centers expanded and grew together. Photo (c.) shows a common phenomenon of apparently reduced anhydrite nodule size and associated pyrite rich zones (black) which radiate outward and upward from the remnants of the nodule.
Nodular anhydrite may occur in large enough quantities to occasionally form beds. Evidence comes from density-neutron logs which show one to three anhydrite layers (approximately 8-10 feet thick each) in a number of wells in the area (Exxon #1 Bush 25-3, Section 25, Tesoro #1 St. Regis 27-5, Section 27, both in 1N-8E Escambia, Alabama). Sigsby (1976) described anhydrite layers and extensive, porous collapse breccias in cores from both Big Escambia Creek and Jay Fields.

Poikilotopic anhydrite is abundant throughout the lower Smackover member. The size of the crystals is related to the intergranular pore size (Figure 8 b and c). Where porosity is low, crystals are small. Where large interconnected pores are present, crystals may grow to several centimeters. Although replacement of sediment is common, nucleation apparently takes place in voids. As uninhibited growth proceeds beyond voids some minor incomplete replacement of carbonate occurs. The crystals are perfectly preserved with no compaction effects as discussed in association with the nodules. It is uncertain whether these anhydrite crystals are syngenetic with the nodular anhydrite. Similar poikilotopic crystals of gypsum were described in recent sabkha sediments by Illing and others (1965).

The pellet-peloid packstone facies seems to have formed in intertidal and shallow subtidal environments. The abundance of fossils and homogeneity of the packstones suggest intense burrowing. Badon (1973) suggested that the spongy oncolites may be analogous to shallow water, low energy algal biscuits in Bermuda (Gebelin, 1969). If so, the spongy oncolites indicate low energy, shallow water
conditions with restricted circulation. Similar interpretations were made by Sigsby (1976); Bradford (1984) and Sailer and Moore (1986). The scattered intervals of leached pellets may indicate minor subaerial exposure, which would aid in restricting circulation Sigsby (1976). Sigsby also described thick intervals of collapse breccias in Jay and Big Escambia Creek as an indication of subaerial exposure. Perhaps the best measure of water salinity is the frequency of anhydrite nodules which likely formed as gypsum penecontemporaneously with deposition. For gypsum to precipitate, seawater must be concentrated by evaporation three and one-half times its normal salinity. The frequency of anhydrite nodules observed may indicate periodic low supratidal conditions as those described by McKenzie and others (1980) in the Persian Gulf. If the anhydrite nodules formed in subtidal conditions, a barrier of some sort located perhaps southwestward the area of study may have existed to form an area wide restricted lagoon.

A laminated wackestone facies (limestone or dolomite) occurs within the pellet-peloid facies. Unlike the laminated mudstones at the base of the Smackover these laminites are hydrocarbon rich (cuttings show dull fluorescence with poor trichlorethane cuts) and occur randomly in the section. They are commonly black with an \( \text{H}_2\text{S} \) smell on a fresh break, and contain assorted bioclasts, some of which are believed to be multichambered, planktonic forams. The laminae are typically bounded by microstylolites which are less parallel to each other than the ones in the laminated mudstone facies (Figure 8 a). Allochems include pellets, brachiopods, thin crinkled-shelled molluscs and planktonic
forams probably of the sub-family Guembelitriiae and genus Gubkinella. The intervals vary in thickness from 6 inches to 12 feet and are present in all of the wells studied. The thickest interval observed (60 feet) was cored south of Blackjack Creek Field in the Belco #1 Mitchem, Sec. 23, 2N-28W, Santa Rosa County, Florida (Figure 10). The Belco well is thought to occupy a more basinward position relative to Jay Field because it has the thickest total Smackover section (480 feet) in the area (Figure 12).

The black laminated wackestones were deposited in a subtidal environment of deposition in perhaps deeper water than any other Smackover facies for the following reasons: (1) association of planktonic forams, (2) laminations are devoid of any indication of current or wave energy, (3) euxinic black color and smell of the rock, and (4) relative basinward position of the Belco Mitchum well where it is apparently thickest. This facies was similarly described and interpreted by Bradford (1984) who recognized a thicker development in depositional low areas. This facies is also the most likely source of Smackover hydrocarbon in the area. Recent studies show similar chromatograph signatures between Smackover rock derived kerogen and crude oil in Mississippi, Alabama and Florida (Sassen and others, 1987; Sassen and Moore, 1988). Recognition of this facies or any other lower Smackover facies with electric logs is not possible.

Upper Smackover Member

The upper member of the Smackover Formation varies from 110 to 235 feet in thickness. It is composed primarily of two distinct lithofacies; the lime pellet wackestone and the moldic grainstone facies. Of the two, the lime pellet wackestone facies is of greater
Figure 12.

Smackover isopach map of Jay-Blackjack Creek area. Upper Smackover grainstones cause thicker section in the fields; mudstones-wackestones cause the thick near Belco Mitchum well. See Plate VIII for a more detailed Smackover isopach map of the Jay area.
aerial extent. Its thickness increases away from the grainstone areas as exemplified by the Exxon Hart well in Figure 6. The second and most important facies is the moldic grainstone facies. It is completely dolomitized in the vicinity of producing fields and provides the major porous reservoir rock in the area (Figures 4, 5 and 6).

Lime pellet wackestone facies: The lime pellet wackestone facies is the most extensive of the upper Smackover facies. It is best developed in the Chevron Scott and the Exxon Hart where it is 110 and 200 feet thick respectively. It represents the entire upper Smackover in those two wells (Figure 6). Fine peloids (0.040 mm) are the most common constituent (Figure 13 a) but larger peloids and Favreina sp. pellets exist throughout. A dark brown, mud supported fabric is characteristic of this unit, though soft sediment compaction occasionally mimics a grain supported texture. Laminations are seldom seen but compaction of sediment while soft occasionally creates parallel microstylolites which mimic depositional laminations. The lack of bioturbation is in marked contrast to the lower member. Delicate echinoids and brachiopods are occasionally preserved unbroken. Echinoid and brachiopod fragments are ubiquitous but never exceed a few percent of the rock volume. Other fossils in decreasing order of abundance are ostracods, molluscs, encrusting bryozoans, siliceous sponge spicules, oncolites and multichambered planktonic forams. Sponge spicules were recognized only in the Exxon McCurdy and Exxon Swift wells and occur in the middle portion of the member. The spicules are biaxial, hollow and composed of granular microcrystalline (GMC) chert. Some
Figure 13.

Lime pellet wackestone facies—Upper Smackover

a. Pellet wackestone with somewhat higher than average number of allochems. Note coarsely crystalline nature of the dolomite replacing the peloids and that the mud is aphanocrystalline (not microspar) which is characteristic of mud supported rocks located some distance from gainstones. (EHa 15518, Plate III; 40x, open light).

b. Scattered dolomite rhombs in mud supported matrix. This sample was just below porous dolomitized grainstone (EMc 270, see Plate II; 250x, open light) and mud aggraded to microspar, which is a relationship frequently seen.
spicules are over a millimeter in length. Planktonic forams appear most often as 10 to 30 micron spheres but multichambered forms are over 100 microns in length. Though very scarce, the forams occur in all wells except the Exxon Swift and are most abundant in the lower parts of the member. Oncolites and encrusting bryozoans occur, but are very scarce.

The pellet wackestone facies was probably deposited in a low energy, subtidal, environment. The paucity of fossils and lack of burrows is perhaps due to a greater rate of accumulation compared with the lower Smackover member, or more restricted subaqueous conditions. The presence of sponges, planktonic forams and unbroken delicate fossils suggests very low energy, subtidal conditions. Though diagenetic and not depositional, the presence of scattered dolomite rhombs and discoid gypsum masses are possible indicators of higher than normal salinities at the time of deposition. Badon (1973) described discoid anhydrite in a similar facies in Mississippi as being indicative of an intertidal setting. However, discoid gypsum is described by Hardie and Eugster (1971) as being of subaqueous origin. The discoid gypsum in the upper Smackover in this case is believed to have formed subaqueously during periods of higher salinity.

Grainstone facies: The highly porous and permeable grainstone facies is dolomitized and is present in all of the producing wells studied (Figure 6). The grainstones extend south of Blackjack Creek Field (Figure 7) but their development is thickest in the vicinity of Jay (Sigsby, 1976). Hand specimen color is black from oil which coats all pores. Bedding features are generally
absent except for a few feet of crossbedded grainstones which occur at the top of the Smackover in the Exxon #15 W. St. Regis.

The thickness and distribution of oolites is shown in Figure 7 and is in accordance with the observations of Bradford (1984) in Big Escambia Creek and Ottman and others (1973) in Jay Field. Figure 7 and Plate XI are maps which closely approximate the distribution of all grainstones including not only oolites but other mixed allochem dolomitized grain supported reservoir rock as well. Of primary importance to the dolomitization question is not just the distribution of oolites but any rock which had good primary porosity and permeability at the time of burial. From these maps three important observations can be made: (i) grainstones are distributed in an arcuate discontinuous belt concave to the southwest through the three fields (Big Escambia Creek, Jay and Blackjack Creek); (ii) the porosity pinches out due to a primary depositional facies change (to carbonate muds) in an up dip direction at Jay (northwest to east) and Big Escambia Creek Field (up dip to the north and east); (iii) lime mudstones separate Big Escambia Creek Field and Jay Field (Plate XI) which indicates the grainstones were probably hydrologically isolated from each other during the Jurassic as well as the present.

Most of the grain supported rock in the study area was dolomitized to completion (Sigsby, 1973; Wagner, 1978; Lomando, 1979; Powell, 1984; Koepnick and others, 1985; Lloyd and others, 1986; Saller and Moore, 1986; and Mitchell Tapping, 1988). The dolomite is a coarsely crystalline mosaic which generally obscures the original fabric (Figure 14 a, b and c). Extensive thin section examination, however, has revealed relict ooid cortices (Figure 14 b)
Figure 14.

Upper Smackover - Grainstone facies
a., b. Dolomitized, oolite grainstone with outer cortex preserved. Coarsely crystalline dolomite probably replaced the original (aragoitic) ooid as opposed to a low Mg calcite oomoldic rock fabric. (a. = HS 15469 and b. = HS 15649)
c. Hints of internal structure are occasionally preserved in an oomoldic fabric. Note concentric pattern where outer rim represents the outermost ooid cortex or an early isopachous cement. (Pennzoil Cooley 15214)
within dolomite crystals in many of the wells studied. The concentric allignment of dolomite crystals (Figure 14 c) may represent either the advanced stage of selective dolomitization of oolite cores and cortices (similar to fabrics illustrated by Moore and Druckman 1981) or the dolomitization of ooid remnants after extensive meteoric dissolution. Finally, the range of the original grain sizes in the upper Smackover at Jay Field are similar to the grain size range of Jurassic Smackover ooids from South Arkansas and modern ooids described from Joulters Cay (Harris, 1979) (see Figure 15 this paper). It is concluded that much of the porous dolomite reservoir rock of Jay and Big Escambia Creek were originally ooid grainstones.

In addition there are dolomitized grainstone in the Jay area which seem to have been originally finer grained (0.18 - 0.4 mm). These rocks are well sorted and unrecognizable in thin section as far as grain type (Figure 16 a). These units may have been winnowed pellet grainstones (Sigsby, 1976), but alternatively, they are similar to the particle size range of superficial ooids (Bissell and Chilinger, 1967; Badon, 1973).

A few coated echinoid, brachiopod and mollusc fragments are the only fossils recognized in this facies. Rhodolites and oncolites are rare, as the grainstones are composed of moderate to well sorted spherical grains with a unimodal size distribution.

According to Ball (1967) the depositional environment of a grainstone sequence should be a function of grain type, setting and the geometry of the unit. The porosity isopach maps (Figure 7, Plate XI) give a general indication of the distribution, but not the
Figure 15.

A comparison of approximate grain size ranges of Jay area grainstones and oolite grainstones of South Arkansas, Smackover (this study) and Jolters Cay, Bahamas (Harris, 1979). Allochems of the Jay area moldic fabrics compare favorably with grain size range of Holocene and other known Smackover ooids.
Figure 16.

Upper Smackover dolomitized grainstone with unrecognizable grains. (HS 15714)

a. Very common fabric with oolite size grain ghosts.
b. All that commonly remains is either the outer ooid cortex or a rind of early isopachous cement.
geometry of individual grainstone units. Regardless of grain type or unit geometry, the grainstone facies does represent a high energy environment of deposition such as a shoal complex which developed over salt related positive bathymetric features. Stacked shoaling upward cycles are present in the massive 150 feet of grainstones in the Exxon Swift. The thicknesses of the individual cycles in the Exxon Swift (see Plate V) are 12, 25, 65 and 45 feet thick from the base upward. In each case the muddy sediments which separate the cycles are poorly developed and difficult to recognize. However, these thin muddy breaks are believed to represent either supratidal sediments which are shown to cap shoal sequences (Moore, 1972; Handford, 1978) or subtidal muds which commonly occur at the base of shoal cycles (Wilson, 1975; Moore, 1989).

Pellet packstone - anhydrite sequence (Uppermost Smackover sequence): By convention the top of the Smackover is placed at the base of the massive Buckner anhydrite. However, the uppermost part of the Smackover, observed here to be 5 to 40 feet thick, does contain nodular anhydrite layers within the dolomitized peloid wackestones, packstones and grainstones. The dolomite is not as coarsely crystalline as the underlying dolomites. Commonly the thin anhydrite layers (3 to 8 feet thick) do not show up on density-neutron logs (Plates XIV, XV) or cuttings and the dolomites are porous, both of which make this zone indistinguishable from the rest of the upper Smackover on electric logs. This uppermost Smackover interval was recognized by Ottman and others (1973) as "the micritic-finely crystalline dolomite unit". It is recognized in the two Jay Field wells and the Exxon St. Regis well near Blackjack Creek
Field. The thicknesses are 32, 20 and 7 feet in the Humble Shell, Exxon Swift and Exxon #15 W. St. Regis respectively (Plates IV, V and VI). The interval was not cored in the Big Escambia Creek, Exxon McGurdy well examined in this study.

Nearly half of the uppermost Smackover sequence consists of grainstones. They are composed of well preserved and easily identifiable ooids (0.18-1.0 mm. in diameter), composite grains and peloids. The dolomite is finely crystalline (usually 20 μm) which accounts for the better fabric preservation compared to the underlying upper Smackover grainstones. Isopachous cements (Figure 17 a) composed of clear crystals, are abundant and so well preserved that cement compromise sutured boundaries remain distinct. Porosity is intergranular, moldic and intercrystalline and all three wells produce oil from this facies in spite of abundant, pore filling, poikilotopic anhydrite cement. Small scale cross beds occur in these uppermost grainstones in the Exxon #15 W. St. Regis.

Pellet wackestones and packstones generally occur as a transition between grainstones and nodular anhydrite layers. The wackestones and packstones are medium brown and poorly laminated. Milk-white nodules of felted polycrystalline anhydrite are abundantly scattered throughout the pellet wackestones-packstones. Sedimentary laminations bend around nodules indicating displacive growth which predates lithification. Occasionally nodule growth is extensive forming layers 6 inches to 3 feet thick of nodular mosaic anhydrite (see Plate IV and V) (terminology from Maiklem and others, 1969). Poikilotopic anhydrite crystals fill pores, partly replacing host rock, and are more abundant than in any other Smackover facies.
Figure 17.

Uppermost Smackover dolomite
a. Typical grainstone, finely crystalline dolomite, with isopachous cement preserved. This rock has porosity and permeability equal to the upper Smackover grainstones. (HS 15591; 40 x, open light)
b., c. Polymictic breccias probably formed at near surface conditions. (b. = EStR 16046; c. = HS 15618) Angular clasts vary widely in fabric and dolomite crystal size.
Fossils are scarce in this sequence. A few mollusc fragments, benthonic forams and echinoid fragments are the only fossils present. They may occur as nuclei of algal oncolites.

The interval from 15612-615 just above the breccia in the Humble Shell well consists of grainstones to packstones with thin micrite layers or crusts which appear to be similar to algal laminated supratidal sediments described by Davies (1970). However, it is also possible that these micrite layers are poorly developed caliche crusts (Choquette, 1968). Exposure surfaces with caliche are common in backshore sediments which cap beach sequences (Moore and others, 1972).

Below the anhydrite layers near the base of the uppermost Smackover, breccias (Figure 17 b and c) were found in two of the wells: the Humble Shell on the western flank of Jay Field (Plate IV) and the Exxon St. Regis near Blackjack Creek Field (Plate VI). Both breccias are 6 inches thick, polymictic and composed of all size clasts both rounded and angular (Figure 17 b and c). The lithology of individual clasts varies from brown mudstones to grainstones. Black coatings are on the upper surfaces of numerous clasts. White coarsely crystalline anhydrite fills much of the remaining pore space.

The breccias may provide evidence for possible subaerial exposure. The two plausible origins for the breccias are either solution collapse from loss of evaporites or diagenetic terrain soils similar to those in the Ellenburger dolomite described by Loucks and Anderson (1980). If the Humble Shell breccia is from solution collapse, dissolution is required before the unaffected overlying
anhydrite layers were deposited. The diagenetic terrain soil idea may receive additional support from the occurrence of wavy layers and blackening along surfaces of clasts (Ward and others, 1970; Folk and others, 1973). Detailed features such as root hairs and circumgranular cracks are lacking. Breccias up to 11 feet thick were reported from an equivalent interval in Blackjack Creek Field in two of the wells studied by Wagner (1978). The breccias were further discussed by Mitchell-Tapping (1988) who found breccias in a third well and considered their origin to be related to leaching by meteoric waters. It is interesting to note the position of the brecciated zone described by Mitchell-Tapping (southwest flank of the structure). If regional dip is eliminated thus restoring the structure to its pre-Buckner position, the brecciated zone would occupy the crest of the paleo structure.

Though unreported by Ottman and others (1973) or Sigsby (1976), future studies may disclose similar breccias at or below the base of the uppermost Smackover across Jay Field. The soil interpretation as opposed to solution collapse would perhaps imply that a few, major periods of subaerial exposure rather than more numerous, minor periods developed in the grainstone areas prior to Buckner deposition.

The uppermost Smackover sediments were deposited in arid high intertidal and low supratidal environments. The general vertical sequence of grainstones overlain by muddy dolomites and evaporites is similar to carbonate beach sequences described by Moore (1972) and Handford and Moore (1976). The grainstones represent the last stages of shoaling possibly as an upper foreshore (Moore 1972)
beach or tidal channel sand. Rim cements are common in such settings. The wackestones-packstones with interbedded anhydrite probably represent tidal flat sediments (backshore) deposited in high intertidal to low supratidal environments. The nodular anhydrites are similar to those described on the Persian Gulf sabkhas by many authors (Kinsman, 1966; Butler, 1970; McKenzie and others, 1980). The paucity of fossils is compatible with the restricted conditions found in supratidal environments.

Lithology and Depositional Environments - Buckner Member

A total of 143 feet of Buckner core was described from five of the six wells studied. The general vertical sequence is composed of massive nodular mosaic anhydrite of varying thickness which overlies the Smackover carbonates (Plates I, III, IV, V, and VI). The anhydrite is overlain by either massive salt, laminated anhydrite interbedded with salt stringers and quartzose clastic material or dominately quartzose clastic material interbedded with evaporites. The thickness and distribution of the Haynesville-Buckner evaporites is related to subtle movements of Louann salt (discussed in "Depositional History").

Anhydrite and Dolomite

The lower Buckner unit is composed of white-gray, felted crystal, nodular mosaic anhydrite (terminology from Maiklem and others, 1969) commonly referred to as "chicken wire", with varying amounts of brown dolomite. The anhydrite thickness varies from 8 feet in areas of thick grainstone development (Plates IX, XI, XII - XV) to 70 feet in depositional low areas (also areas of present day
structural lows) where Smackover carbonate mudstones accumulated. The base of the nodular mosaic anhydrite is sharp and usually easily picked on electric logs. The Chevron Scott and Exxon Hart (Plates I and III respectively) are good examples. Scattered pyrite, 1-100 μm euhedral crystals of clear dolomite, and 0.1-0.8 mm. anhedral crystals of calcite with cloudy centers are occasionally found floating within the nodular, felted crystal anhydrite mass. Irregular patches of large blocky anhydrite crystals are slightly greater in abundance than calcite and dolomite.

Closely associated with the nodular mosaic anhydrites are thin beds (2 feet or less) of dolomitized mudstones to packstones, best exemplified in the Exxon #15 W. St. Regis, where displacive nodular anhydrite growth is less extensive (Plate VI). The dolomites are microcrystalline (1-20 μm crystals) which usually preserves rock fabric. _Favrina_ sp. pellets, a few ostracods and benthonic forams, mollusc shells and oolites are the only recognizable allochems. The dolomites are always associated with numerous felted crystal anhydrite nodules in which packstones are often squeezed between and around grains. Large poikilotopic anhydrite crystals are also present which may comprise over 50 percent of the rock. Occasionally, euhedral to subhedral dolomite crystals (+40 μm) are disseminated in the dense, laminated (Figure 18 c), finely crystalline anhydrite layers.

The nodular anhydrite in the Exxon #15 W. St. Regis and the Exxon Scott is overlain by 10 to 15 feet of multicolored laminae of clay, silt, fine sand and microcrystalline anhydrite (Figure 18 a). The laminations on occasion are parallel with numerous individually
Figure 18.

Buckner Evaporites
a. Laminated anhydrite of probable subaqueous origin. (Exxon Scott 15490)
b. Silty claystone with pseudomorphs after halite. (P. St.F. 15280)
c. Silty anhydrite with abundant rounded (detrital ?) anhydrite clasts. (Exxon Scott 15500)
graded laminae (2 mm. thick) with sand at the base fining upward to micaceous silt and clay. Many layers possess scattered plant material and rounded clay, silt and anhydrite clasts (Figure 18 c). The laminated bedding may be interrupted by 6 inches to one foot of poorly sorted silt and clay clast rich sediment probably reworked by storms. Slump structures and other soft sediment deformation features are found throughout. The overlying sediments are mostly red-pink sands with abundant shale clasts. Red, green and black claystones are poorly bedded, possibly exhibit dessication features and interfinger with gray-white-pink nodular mosaic anhydrite. However, pink-red fine sandstones predominate.

Halite

Halite is present in the Exxon Scott as large hopper crystals and vug fillings at the base of the sandy section (Figure 18 b). Generally, the salt stringer interval (see Figure 3 and Plate X), which is thickest (over 300 feet) over Flomaton Field, is hazardous to drilling operations because of washouts caused by fresh water based drilling mud systems. Monitoring the total chloride content of the drilling mud also makes the salt interval easy to recognize. When the salt occurs as stringers the dual induction laterolog (DIL) log response shows extremely low resistivities (Figure 3). If the salt is massive, excessive washout occurs and DIL log records as featureless, wavey curves. The salt stringers consistently occur just above the massive, dense Buckner anhydrite which is composed of both nodular mosaic and laminated anhydrites.

The Buckner section examined in all of the study wells except the Exxon McCurdy actually represents a number of
sub-environments mostly high intertidal, supratidal, and restricted subaqueous. Nodular mosaic anhydrite is a product of accretionary growth which displaced the host sediment to such an extent that the original sediment cannot be identified. Felted crystal nodular anhydrite and gypsum similar to the Buckner was described (Kinsman, 1966; Shearman, 1966; Butler, 1969) in Holocene supratidal sabkha flats along the Trucial Coast. The Gigas Beds in northwestern Germany, as described by Schmidt (1965), is a late Jurassic analogy. Nodular mosaic anhydrites also may be a subaqueous lithotope product. Warren and Kendall (1985) characterized sabkha versus salina environments and generally favor the salina model for thick nodular mosaic anhydrite sequences. South Australia salinas cited have no surface connection with the ocean. Marine recharge occurs in the subsurface. This produces pure, thick evaporite sequences with no clastic influx. The result is a "bulls-eye" evaporite with a gypsum core and lime mud flat periphery. Dolomite is a rare exception but may occur sparsely on the outer fringe of the lime mud flats where meteoric waters interact. They also state that stacking sabkhas, which would require a slow rise in relative sea level, could explain thick nodular mosaic anhydrite sequences.

Armed with numerous recent studies (Hardie and Eugster, 1971; Schreiber and Kinsman, 1975; Warren, 1982; Sonnenfeld, 1984; Shearman, 1985; Warren and Kendall, 1985) of original depositional sulfate mineralogies, diagenesis and stratigraphic models, Mann (1988) analyzed the Buckner anhydrites in the Hatter's Pond - Chunchula Field area. He divided the Buckner into three facies and
interpreted the massive nodular mosaic anhydrite (selenite facies) to be subaqueous in origin.

Where upper Smackover grainstones in the Jay area are thin to absent (sites of paleotopographic lows) the overlying nodular mosaic Buckner anhydrites are probably of subaqueous salina origin. However, the nodular mosaic anhydrites over paleotopographic highs or thick grainstone areas (over Jay-Big Escambia Creek and Blackjack Creek Fields) are considered more likely to be supratidal by the following: (1.) Warren and Kendall (1985) noted that sabkhas generally have as many dolomite as anhydrite beds which is also observed here in the Exxon St. Regis (Plate IV, 16015-16040) Exxon Swift (Plate V, 15410-15440) Humble Shell (Plate IV, 15570-15615) and many other wells studied by Powell (1984) and Wagner (1978); (2.) no lime muds were observed in the uppermost Smackover-Buckner sequence in the Jay area. Lime carbonates are closely associated with the salinas (Kinsman, 1969; Warren and Kendall, 1985); (3.) if sabkha sedimentary cycles are generally one meter thick (Warren and Kendall, 1985; Lowenstein (1987)) then two or three stacked cycles would explain the volume of nodular mosaic anhydrite in the wells studied (see Plates I, IV, V and VI).

Stacked sabkha cycles have been previously described in the Buckner in the vicinity of Jay Field. Lowenstein (1987) recognized a dozen cycles he thought to be sabkha in approximately 100 feet of Buckner nodular anhydrite and dolomite from the Conoco #2 Higgins, Mobile County, Alabama, just west of Mobile Bay. The relative proportions of dolomite beds to anhydrite beds he described also fit the Warren and Kendall (1985) criteria for a sabkha sequence but
Lowenstein does mention pseudomorphs of crystal clusters suspected to be from localized subaqueous pond environments.

The Buckner nodular anhydrites which overlie thick Smackover grainstones, therefore, are considered to be predominately of supratidal origin. The interbedded peloidal wackestone to grainstone dolomites may either represent storm overwash or the reappearance of shallow, restricted marine lagoons.

The laminated anhydrite (probably originally gypsum) and claystones were deposited in a subaqueous manner probably in pans or salinas located on tidal flats similar to those described by Phleger and Ewing (1962), Kinsman (1969), Handford (1981), Lowenstein (1987) and Mann (1988). Storms likely blew in quartz mica sand, silt and dust which by gravity settling formed the cyclic graded laminae similar to those described by Kinsman (1969). The laminated anhydrite is microcrystalline (2 μm crystals) with crystallites having a common orientation revealed under polarized light and the gypsum plate. Kinsman (1969) describes subaqueous salina gypsum with c-crystallographic axis nearly horizontal. Vertically oriented, poorly sorted rubble zones observed may be the result of gas or water escape. They may also represent collapse breccias (salt dissolution) somewhat analogous to chaotic mudstones associated with salt pan sediments in the west Texas Permian (Handford, 1981). The green color commonly associated with claystone laminae may further indicate subaqueous halite precipitation. Low Eh brines reduce ferric iron in clays at Bristol Dry Lake producing green-black clays in the center of playa whereas oxidized red clays are more prevalent along frequently exposed playa periphery (Hardie and Eugster, 1971).
Occasional small scale folds represent soft sediment deformation as clays compact, dewater and become hydrostatic. A salt pan phase caps the salina sequence as sands and shales of a low relief prograding delta sequence buried the massive evaporites. The "bulls-eye" salina model (Warren and Kendall, 1985) does not quite fit the Buckner for the lack of periphyrally associated lime mudestones and high coastal dunes. The marine waters needed to supply the Buckner salinas probably came from one way surface tidal channels which circum-navigated the higher (supratidal) areas.

A delta complex much like the Ord Delta of Northern Australia (Coleman and Wright, 1975) blanketed the entire area. Bifurcating, possibly ephemeral, channels carried sands southwestward over a significant distance (probably tens of miles) to the delta front. High tides flooded the interdistributary areas creating vast flats of supratidal sediments. Low tides created vast mud cracked flats with evaporites in the interior parts. The tidal range is 15-20 feet near the Ord River Delta. A similar tidal range during Buckner deposition could affect an area much larger than the Jay-Big Escambia Creek complex.

Depositional History

A series of maps (Plates VIII-XI) and cross-sections (Plates XII-XVI) are used to demonstrate the stratigraphic distribution of the major facies (grainstones, mudstones, massive anhydrite and salt) and the paleo-structural elements which controlled their occurrence in the Jay-Big Escambia Creek area. A comparison of the maps reveals an arcuate pattern of paleo highs and lows which began during upper Smackover deposition and which
apparently were persistent (graben development) throughout the Cretaceous as seen on proprietary seismic sections. The lower Smackover is fairly uniform in appearance and thickness which indicates a lack of significant bathymetric relief during its deposition. A comparison of the total Smackover isopach (Plate VII) to the upper Smackover porosity isopach (Plate IX) and Buckner isopach (Plate IX) show thick Smackover porosity (dolomitized grainstones) and thin Buckner over areas of thick Smackover (paleo-highs), and conversely, thick Buckner with little or no underlying Smackover porosity (dolomitized grainstones) over areas of thick Smackover (paleo-lows). The pattern repeats at Big Escambia Creek, Jay and Blackjack Creek Fields with the exception of Flomaton Field (Norphlet gas wells in the northern half of Township 1 North - 8 East). The Flomaton area is structurally high today (Plate VII) but it was obviously bathymetrically low during Smackover deposition (Plate VIII). Thick Buckner anhydrite should be expected over Flomaton Field (Plate IX) but it was such a negative area that salt deposition (Plates X and XV) compensated for the thin Buckner sequence. Again, the combination of thin Buckner, thick Smackover and thick Smackover porosity (grainstones) over the paleo-high areas, and thin muddy Smackover with thick Buckner anhydrite and salt stringers in the low areas is a persistent pattern in the area. The fact that the low areas continued to be low through geologic time is not coincidental. It leaves little doubt that the upper Smackover and Buckner stratigraphy was affected by Louann salt movement and that the graben present today marks a hinge-line north of which
Louann salt is thin to absent. The area south of this hinge-line was subject to Louann halokinetics.

**Lower Member Smackover Formation**

Initial Smackover deposition consisted of low-energy carbonates which accumulated due to a marine transgression over Norphlet sands. The physiographic high areas received laminated, (algal mat as interpreted by Sigsby, 1976 and Bradford, 1984) carbonates while nearby lower spots received restricted intertidal sediments. The small volume of terrigenous material in the basal Smackover everywhere may suggest that large areas of Norphlet sands were quickly covered by the low energy carbonate muds. Conditions quickly equalized over the entire area as is indicated by the thin and spotty distribution of the laminated mud facies and the regionally uniform thickness of the pellet-peloid packstone facies (Figure 6 and Plates XII-XV). A slight rise in sea level brought almost the entire Jay-Big Escambia Creek area into intertidal shallow-water conditions. The collapse breccias and leached pellet fabrics are considered evidence for subaerial exposure (Sigsby, 1976). The vertical and lateral persistence of the lower Smackover lithology suggests that sediment accumulation kept pace with subsidence. Such shallow water conditions should be greatly affected by the most subtle movements of the Louann salt (halokenetics). Subtle salt movements may be responsible for sporadic subaerial exposure and for creating depressions where the subtidal black laminated wackestones may accumulate. This could explain the repetitive and random occurrence of the laminated wackestones, which are thicker toward the south in the Belco Mitchum well (Figure 12),
and near Flomaton Field (Bradford, 1984). The lower Smackover stratigraphy in the Big Escambia Creek area is discussed in greater detail in Bradford's (1984) study.

**Upper Member Smackover Formation**

A rise in sea level during mid-Smackover deposition coupled with subtle Louann salt movement created two contrasting depositional environments which produced totally different sedimentary sequences compared to the lower Smackover member. The bathymetric low areas were the site of low energy, subtidal muds for the duration of Smackover deposition (most of Township 1 North - 8 East, Escambia, Alabama) (Exxon Hart; Plates III and XV). The high areas were sites of shallower water and higher energy resulting in the formation of oolite and peloid grainstone shoal complexes. The two Jay Field wells and Plate XI, as well as previous studies, indicate that grainstones are thickest in the center of the field (Figure 6; Ottman and others, 1973). The thicker total Smackover section (Plate VIII) in the grainstone areas over Jay Field is likely a result of subsidence keeping pace with grainstone generation. The lack of well developed supratidal sequences capping the shoals within the grainstones suggests that the bars seldom reached sea level either due to subsidence or high energy conditions causing rapid sediment redistribution. However, at the climax of Smackover deposition, the entire Jay grainstone sequence is capped by a tidal flat, supratidal sequence. This sequence (Plates IV, V and VI) was referred to as the uppermost Smackover in the section on lithologic descriptions (also see Plates XIV and XV). Widespread moldic porosity is an indication that the upper Smackover grainstones were exposed to meteoric waters
over Jay and Blackjack Creek Fields prior to Buckner deposition. During uppermost Smackover deposition and particularly during the subaerial exposure, the subaqueous conditions in low areas must have been even more restricted, as indicated by two feet of ostracoid-pellet mudstone immediately below the Buckner contact in the Exxon Hart and the abundant pseudomorphs after gypsum (Plate III).

**Buckner Member**

The precipitation of supratidal nodular anhydrite (Plates IV, V and VI) began over grainstone supported topographic highs while subtidal nodular gypsum began to form in the low areas (see Plate XIV). At Jay and Blackjack Creek the formation of Buckner nodular mosaic anhydrite was a continuation of the uppermost Smackover supratidal sequence. During the latter stages of Buckner anhydrite deposition, salinas developed more extensively in low areas and were sites of subaqueous laminated anhydrite, sand, silt, clay deposition commonly with halite capping the sequence. When salinas over the topographic highs were dry, thin beds of nodular anhydrite and halite formed, the halite being dissolved by subsequent flooding. The salinas in the low areas accumulated thicker salt deposits (Plate X). In the Flomaton Field area (1N-8E, Escambia, Alabama) and in the east-west oriented trough just north of Big Escambia Creek Field (Plates IX and X) thick salt (100+ feet) overlies thin (8-10 feet thick) Buckner nodular anhydrite due to more rapid relative subsidence. A southwestward prograding arid delta complex covered the massive Buckner anhydrites and salts with thin sand sheets. The interdistributary bays were once again sites of supratidal
sedimentation, this time dominated by fine terrigenous clastics for the remainder of Haynesville deposition.

It is important to note that deposition of the Buckner anhydrite was a regionally continuous (laterally) event. Detailed gamma ray correlations demonstrate the upper Smackover grainstones to be a facies of upper Smackover mudstones (see Plates XII, XIII, XIV and XV). The upper Smackover grainstones were always found to be stratigraphically separated from the lower Haynesville salt stringers by the regionally continuous Buckner anhydrites. This relationship is important for subsequent discussions of Mg$^{++}$ rich water sources for dolomitization.

Although considered of minor importance, it should be noted that there are two slightly different correlations for the uppermost Smackover. The uppermost Smackover dolomites may be a facies of the lime mudstones (upper Smackover) as in Figure 19-A or it may be laterally equivalent to Buckner anhydrites as drawn in example B. While uppermost Smackover supratidal grainstones-packstones and nodular anhydrites occupied the highs it may be more likely that lime mudstones to occupy the lows (Figure 19-A) rather than subaqueous evaporites.

**Diagenetic Fabrics**

This section is based entirely on petrographic observations. The chemistry will be discussed and summarized with the petrographic relationships in a subsequent section entitled "Diagenetic History".
Figure 19.

Two possible correlations of the uppermost Smackover dolomites (grainstone above dashed line). Cross-sections (Plates XIV and XV) were drawn with alternative B in mind.
**Isopachous Rim Cements**

**Lower Member-Smackover Formation:** The little isopachous rim cement present in the Lower Smackover member occurs in the dolomitic limestones near the top of the member. A few samples were found where peloids and the walls of vugs are lined with bladed to equant microcrystalline calcite cement. Microcrystalline and coarse rhombic dolomite cements were also observed along pore walls. Occasional samples have three layers of alternating dolomite-calcite isopachous cement. Petrographic relationships could not resolve the origin of these cements. However, similar alternating calcite-dolomite cements of Pleistocene age from the Hope Gate Formation, Jamaica (Land, 1973a) and Late Pleistocene age from Yucatan, Mexico (Ward and Halley, 1985) were thought to be the products of mixed marine-meteoric water precipitation.

**Upper Member-Smackover Formation:** The isopachous rim cements in the dolomitized oomoldic grainstones from the Humble Shell are clear to milky color in contrast to the brownish tint of the dolomite which replaced the oolite grains. The layer of cement thins at grain contacts (Figures 14 c and 20). Prior to dolomitization, it is unknown whether the cements in the upper Smackover dolomite were fibrous, blocky or bladed. Some indication may come from partly dolomitized lime grainstones in the Exxon Scott, Pennzoil St. Forest and Pennzoil Cooley wells. In these wells, oomoldic grainstones have large dolomite crystals within grains and 10-40 um equant, blocky to slightly bladed sparry calcite cement around grains (Figure 20). The blocky calcite has abundant 2-phase fluid inclusions and is petrographically similar to the south Arkansas fabrics in the
Early isopachous circumgranular cements found in upper Smackover grainstones. (P. ST.F. 15,322) Collapsed grains (b.) bladed cement crystals have large two-phase fluid inclusions.
northern fresh water dominated diagenetic zone described by Moore and Druckman (1981) and Stamatedes (1982).

Bladed to equant calcite spar cements occur in Bahamian oolites (Halley and Harris, 1979) and Yucatan reef rocks of Pleistocene age (Ward and Halley, 1985) and are suspected to be of meteoric water origin.

The dolomitized rim cements in the uppermost Smackover of the Humble Shell, Exxon Swift and Exxon St. Regis (Figure 17 a) display sweeping extinction commonly seen in marine fibrous aragonite and magnesian radiaxial calcite cements (Bathurst, 1971; Kendall, 1985; Moore, 1989). This and the polygonal sutures similar to those described by Shinn (1971), suggest a marine origin for at least some of the isopachous rim cements.

The rim cemented grainstones show a low grain density (Figure 20 b) which indicates that the isopachous cements formed early, before physical compaction could occur (after Coogan, 1970; Conley, 1977; Moore and Druckman, 1981; Moore, 1985; Moore, 1989). The early cement in most cases has inhibited grain framework collapse due to dissolution of ooids. Where the cement is best developed (Figure 14 c) porosity is high (+ 30 percent in the Humble Shell well) and compaction is low.

Moldic Porosity and Microspar

Lower Smackover Member: Moldic porosity is the result of selective leaching of the 0.15 mm pellets (Figure 10). Occasionally an increase in porosity is accompanied by an increase in dolomite crystal size (20 μm maximum diameter). Crystals are anhedral except where facing pores. The absence of intergranular
porosity and isopachous cements suggest the leached rock was originally a packstone as in the adjacent nonmoldic dolomites. The remaining walls of leached grains are probably micrite envelopes which survived the dissolution. Dolomitization perpetuates undersaturation with respect to calcite which may result in moldic fabrics (Illings and others, 1965). However, the vast majority of the lower Smackover dolomite shows no signs of leaching. The thin beds of moldic fabrics and chalky textures (microspar) are unique events probably caused by subaerial exposure to meteoric waters. Steinen (1978) described similar fabrics in packstones from the Pleistocene of Barbados which were the result of fresh water dissolution.

Upper Smackover Member: Fabric selective dissolution of ooids is widespread and affects most of the grainstones. Partial dissolution of the ooid is most common. Oolite grainstones almost always exhibit signs of dissolution. Fifteen feet (15445-460) of grainstone in the Exxon Swift mimics a non-moldic compacted grain fabric (also Peazel, 1981), yet good porosity and permeability prevail. Recent and Pleistocene aragonitic ooids from the Bahamas and Florida show fabric selective dissolution which has been interpreted as the result of fresh water leaching (Robinson, 1967; Halley and Harris, 1979). Estimates are that an aragonite ooid grainstone can be converted totally to calcite in 10,000 to 20,000 years (Harris, 1979). A similar origin was proposed for the oomoldic fabrics in the south Arkansas (Moore and Druckman, 1981; Druckman and Moore, 1985; Moore, 1984) and east Texas (McGillis, 1984; Stewart, 1984; Wilkinson, 1984) Smackover. Recent studies (Moore and others,
1986; Swirydczuk, 1988) relate Smackover oomoldic porosity development to original oolite minerology. They conclude oolites with radial structure were originally calcite and resisted dissolution. Oolites with tangential cortex structure or blocky calcite crystals that cross cut but preserve cortical laminae were originally aragonite. Dissolution of ooids is ubiquitous in the Jay-Big Escambia Creek study area. This usually precludes ooid cortex observations. However, some workers may argue an originally aragonitic minerology may be inferred from the presence of the moldic fabrics (Swirydczuk, 1988).

Lime muds near grainstone beds are recrystallized to microspar (5 μm in diameter) (Figure 13 b) which has a lighter color, chalky rock texture and greater permeability compared to unaltered wackestone. Contacts commonly grade over a few feet and microspar exists within as well as between grains. The porosity and permeability in the Exxon McCurdy (Plate II) from 15,280-325 is in a pellet wackestone with dolomitized and leached pellets in a microspar matrix. Numerous solution seams are present. It is, therefore, uncertain which is the permeability causing factor, but again, moldic porosity, dolomite and microspar occur together.

Calcite microspar is strongly suspected to be a diagenetic product of fresh water characterized by low Mg$^{++}$/Ca$^{++}$ (Chafetz and Butler, 1980; Folk, 1974; Choquette, 1968). The close association of microspar with oomoldic porosity may be an indication that they share a common origin (Halley and Harris, 1979).

Uppermost Smackover and Buckner: Moldic porosity in the uppermost Smackover and Buckner dolomites is not as extensive as in
the upper Smackover grainstones. Most of the intercrystalline spaces in the Buckner dolomites are filled by poikilotopic anhydrite and calcite cement. Replacement of dolomite by the calcite and anhydrite cement seems to be minimal as reflected by the sharply defined dolomite crystal boundaries and inclusion free anhydrite. It is felt, therefore, that the mollusc fragments and intragranular spaces now occupied by anhydrite are believed to represent former pore space. Leached peloids and bioclasts are well documented in the high supratidal portions of Persian Gulf sabkhas (Illing and others, 1965), which is the area susceptible to rain recharge (McKinzie and others, 1980).

Blocky Calcite Cement

Blocky-polycrystalline calcite cement is sparse and restricted to the lime packstones near the top of the Lower Smackover member. The blocky crystals assume a pore filling habit in intergranular pores and shelter voids. Crystals are clear, fine to medium crystalline (15-100 μm) and equant (after Folk, 1965). The small cement volume makes it difficult to establish its relationship to other diagenetic features. However, blocky calcite cements commonly preceed the formation of saddle dolomite, and other diagenetically late cements.

Blocky polycrystalline calcite cements alone are not diagnostic of an environment of precipitation. Blocky cements were described in Holocene reef rock of Bermuda (Schroeder, 1974) and were considered to be of marine origin. Deep marine blocky calcite is also described by Moore (1989). Similar cements are considered to be of mixed marine-fresh water origin (Folk, 1974) particularly where
associated with moldic fabrics (Robinson, 1967; Steinen, 1974; Moore and Druckman, 1981; Moore, 1985; Moore, 1989).

Dolomite

Lower Smackover Member: The lower Smackover member is composed of microcrystalline replacement dolomite, coarsely crystalline limpid dolomite and saddle dolomite. The saddle dolomites can be demonstrated to be a late diagenetic product and thus will be discussed separately.

The bulk of the lower Smackover dolomite (probably 95 plus percent) is microcrystalline replacement dolomite with crystals from 1 to 10 \( \mu \text{m} \). The microcrystalline replacement dolomite fabric is not diagnostic of a particular mode of formation; nor does the petrography clarify its timing. Indirect evidence allows us to narrow the possibilities of its timing and origin. The association of anhydrite nodules, dolomite and leached fabric is ubiquitous. The anhydrite nodules are displacive having formed while the sediment was soft. They must also be indicative of evaporative conditions. The nodules are scattered but in some wells they form layers. The leached pellet fabrics could be either the result of meteoric water dissolution (Sigsby, 1976) or a byproduct of dolomite and \( \text{CaSO}_4 \) precipitation. As anhydrite (gypsum) precipitates, the aqueous \( \text{Ca}^{++} \) concentration decreases thus increasing the \( \text{Mg}:\text{Ca} \) ratio. This should trigger dolomite precipitation which, in turn, increases the calcium in solution thereby perpetuating additional calcium sulfate precipitation. It must also be noted here that periodic leaching was moderate so as not to completely remove anhydrite nodules from the underlying sediments. Dolomitization probably was concurrent with
nodular calcium sulfate precipitation with occasional wet seasons which caused leaching. The anhydrite nodules were shown to be a soft sediment occurrence. Therefore, the nodules formed prior to later stages of dolomitization.

Hypothetically, post burial dolomitization may be possible by either past-halite (low in Na, high in Mg) Louann brines migrating updip (Carpenter, 1978; Stoessell and Moore, 1983; Barrett, 1986) or meteoric waters displaced from the Norphlet (Lloyd and others, 1986) or downdip moving meteoric waters from the Cotton Valley sediments (Prather, 1986). However, direct petrographic evidence suggests that lower Smackover matrix dolomitization must occur prior to saddle dolomite and poikilotopic anhydrite formation. The overlying mud rich limestones of the middle and upper Smackover are of regional extent and formed an effective barrier which eliminates the possibility of dolomitizing fluids coming from above. Otherwise, the lime muds would also be dolomitized.

Clear, limpid (Folk and Land, 1975) dolomites line vug and cavity walls in shelter voids and within bioclasts in the dolomitic limestones near the top of the member. These dolomite cements clearly predate saddle dolomite, fluorite and anhydrite. It cannot be determined, however, how early they may have formed.

Upper Smackover Member: The origin of the upper Smackover dolomites cannot be resolved solely on the basis of petrographic relationships. The petrography does, however, give us some basic constraints on their origin.

Dolomite crystals in the upper Smackover average 100 um with a size range from 40 to 120 μm. The coarsest intervals have a
size range of 250-350 um. Crystals which abut each other are anhedral, and those facing pores or other minerals are euhedral. Scattered dolomite crystals in the lime mud facies are euhedral. Intergranular and moldic porosity exist together throughout the facies. A few samples contain dolomite crystals with relict ooid cortices, which confirms a replacement mode for some if not all of the dolomite. Ten miles east of Jay Field in the Pennzoil Cooley well (Figure 12), the isopachous cements probably were originally precipitated as calcite or aragonite and were later dolomitized. Many of the upper member ooids are totally dissolved which suggests that isopachous cementation must at least partially predate total ooid dissolution in order to maintain an open rock fabric. Analogies to this fabric are found in the Smackover occurs in the south Arkansas northern zone of Moore and Druckman (1981), Stamatedes, (1982) as well as in east Texas (McGillis, 1984; Stewart, 1984; Wilkinson, 1984; Moore, 1984; and Moore and others, 1988). The isopachous rim cements could be of either marine or fresh water origin. Poikilotopic anhydrite and rare fluorite and calcspar are the only other cements in the oomoldic grainstones and the dolomite predates all three diagenetic phases.

Dolomite is present throughout the upper Smackover wackestone member either as finely disseminated euhedral crystals replacing mud or as euhedral to subhedral aggregates selectively replacing pellets (Figure 13 a, b and c). As the dolomite crystals in pellets become clustered they lose their euhedral crystal facies except when in contact with calcite. Dolomite crystals in any one sample have a narrow range in size, but the crystal size varies
greatly from sample to sample. Dolomite in this facies seldom exceeds fifty percent of rock volume but as dolomite content increases, so does selective leaching of peloids and recrystallization of the lime mud to microspar, with a corresponding increase in permeability. Dolomite crystals contain numerous tiny inclusions of calcite, which may be either included mud matrix, or dedolomite. Large scale calcitization of dolomite as described by Stamatedes (1982) in southern Arkansas, however, seems to be rare. Petrographic evidence suggests that dolomites predate microstylolites for two reasons. Corroded dolomite crystals are concentrated along microstylolites and rocks without disseminated dolomite in the matrix have no dolomite along associated microstylolites.

Selective dolomitization of pellets and peloids could be the result of mineralogic selectivity, porosity selectivity or crystal size selectivity. A small calcite crystal size in Smackover pellets relative to the surrounding matrix would present greater surface area perhaps affecting the nucleation kinetics of the dolomite.

At this point it is still unclear how the upper Smackover dolomites formed. Any of the popular models (Buckner brine reflux; mixed marine-meteoric hydrology; normal to slightly evaporated Smackover seawater; deep burial) may be argued. The only conclusion that can be reached based solely on petrography is that dolomitization preceeds stylolites and the late cements (fluorite, poikilotopic anhydrite, saddle dolomite, etc.) Additionally, lenticular and dovetail (discoid, Figure 23 a) shaped pseudomorphs
after gypsum contain numerous dolomite inclusions, which indicate some dolomite predated or co-precipitated with lenticular gypsum.

Buckner Member: Dolomite beds represent a small percentage (5%) of the Buckner sediments described and, like the Smackover, offer little petrographic evidence in support of their origin. The dolomite crystals disseminated in dense, impermeable anhydrite formed either penecontemporaneously with deposition or during compaction. Formation in either case was under the influence of CaSO$_4$ saturated brines. The microcrystalline dolomite-pellet, mollusc packstones were associated with abundant anhydrite nodules and thus formed in evaporated seawater similar to the lower Smackover dolomites but under conditions of higher salinity.

Compaction

Compaction in Lower Smackover Member: Numerous laminations, which may not be related to sedimentary structures, occur in the lower Smackover. Crudely laminated dolomites within the leached intervals mimic the laminated dolomitized mudstone facies but are actually the result of mold collapse similar to features described by Conley (1977). Microstylolites are present throughout the member. Microstylolites and swarms of solution seams commonly cause whispy laminations and may be a function of terrigenous clay content (Wanless, 1973, 1979; Moore, 1989). Microstylolites that clearly are not related to clay content are those which concentrically surround displacive anhydrite nodules.

Evenly spaced microstylolites result in a laminated appearance in lime mudstones to wackestones in the Exxon Hart, Humble Shell and Belco Mitchum wells. It could not be determined if the
diagenetic laminations are related to clay content, a particular environment of deposition (tidal flat; subtidal gravity settling) or a simple compactional process. In other words, the stylolites could obscure but reflect an original bedding fabric. Large amplitude (few millimeters) sutured seam stylolites are less numerous and truncate all diagenetic products.

Compaction in Upper and Uppermost Smackover Member: In general, compaction features in the grainstones are rare. Distorted ooliths and isopachous cement shards (Conley, 1977) formed as a result of compaction are only recognized in the uppermost Smackover grainstones. This style of grainstone compaction leaves a fabric of random triangular shaped pieces of intergranular cement similar to those described by Conley (1977) and Zempolich and others (1988). Grain collapse (Figure 20 b) leaves oval or flattened residues. This is characteristically associated with isopachous bladed to equant calcite cement and grain moldic porosity. This type of compaction is believed to be a continuous collapse during removal of intragranular carbonate probably by meteoric water (Robinson, 1967; Clark, 1980; Zempolich and others, 1988). It may also be an indication of dissolution under shallow (tens of meters) burial conditions and phreatic zone conditions (Moore, 1989). Large scale stylolites throughout the member truncate all diagenetic features.

Compaction in the pellet wackestones is in the form of microstylolite-solution seams, compacted peloids and large stylolites. Microstylolites and solution seams commonly bend around rigid bioclasts and allochems (Figure 8 c; 21 a and b; 22 a, b and c) in response to localized pressures. Commonly, small whisps of
insoluble residue are all that remain of compacted peloids (Figure 22 a). Insoluble material along stylolites may include dolomite in addition to organic material and pyrite crystallites. Flattened peloids in the Smackover occur over and under rigid allochems (Zempolich and others, 1988) and in swarms as described by Wanless (1979). The flattened peloids appear to be an early, soft sediment effect caused by localized pressure similar to the above described microstylolites.

Sutured seam stylolites (after Wanless, 1979) are commonly present throughout the section. They occur in every lithology except the anhydrite beds and crosscut all cements.

**Saddle Dolomite**

Saddle dolomite, also referred to as "white sparry dolomite" (Beales, 1971) and "baroque dolomite" (Folk and Assereto, 1974), occurs throughout the member. The crystal morphology is similar to that described by Radke and Mathis (1980) with numerous inclusions, curved crystal faces and characteristic sweeping extinction. It takes a weak aqua blue stain (indicating iron) when treated with potassium ferricyanide (Dickson, 1966). Saddle dolomite usually only occurs in pore spaces, not as a replacement, and is the first of the deep burial cements to precipitate. Single pores commonly have saddle dolomite, poikilotopic anhydrite and calcite which enables the determination of its timing relative to other deep burial cements. It predates fluorite, poikilotopic anhydrite, celestite and calcite. Saddle dolomite occurs within the producing interval of the Exxon Swift well. It also occurs prior to oil migration in Mississippi (Heydare and Moore, 1989) south Arkansas
Figure 21.

Compaction features in the Upper Smackover wackestones. Soft sediment compaction around the tip of a brachiopod shell (EHa 15415) Upper Smackover (a = EHa 15415, b = HS 15705)
Figure 22.

Compaction features upper Smackover wackestones. Sediments bend over tip of brachiopod (a.), show flattened peloids (b.), and bend around rigid echinoderm fragments (c.).
Precipitation of saddle dolomite prior to oil migration is known to occur in other basins (Beales, 1971; Choquette, 1971; Mathis, 1978). In Mississippi, Heydari (1989) found deep burial calcite to predate as well as postdate saddle dolomite precipitation. In south Arkansas and east Texas O'Hearn (1985) and Moore (1985) found saddle dolomite to be the last deep burial cement to precipitate based on petrography and fluid inclusion heating and freezing analysis.

Saddle dolomite is known as a gangue mineral in metal sulfide ore deposits (Jackson and Beales, 1967; Beales, 1971; Choquette, 1971; Radke, 1980; Beales and Hardy, 1980). However, it is also well documented as a common pore-filling cement in carbonate rocks (Beales, 1971; Choquette, 1971; Folk and Assereto, 1974; Radke, 1978; Mattes and Mountjoy, 1980; Dickson and Coleman, 1980; Moore and Druckman, 1981; Moore and others, 1988; to name a few). Its formation at higher temperatures has been alluded to by Radke and Mathis (1981) who consider 60° to 150°C a range of formation. Recent work in the Smackover of south Arkansas (Croft, 1980; Moore and Druckman, 1981; Brock and Moore, 1981; Stamatedes, 1982) southeast Texas (Moore and others, 1988) and south Alabama (Feazel, 1980) demonstrate that saddle dolomite postdates the "early" diagenetic products such as isopachous rim cements, matrix, dolomite, etc. The late diagenetic (deep burial) mode of formation of saddle dolomite observed in this study is compatible with that of the Smackover workers cited above. Its timing must be prior to hydrocarbon migration (Heydari and Moore, 1989).
Saddle dolomite in the upper Smackover member is extremely rare in the pellet-wackestone facies and the grainstone facies. However, the uppermost Smackover facies has minor amounts of pore-filling saddle dolomite which predates the pervasive poikilopic anhydrite.

Sulfides and Sulfates

Sulfides and Sulfates in the Lower Smackover Member: The felted crystal anhydrite nodules are believed to be an early diagenetic product because of associated soft sediment features described in the section on lithostratigraphy and by analogy to nodules in recent Persian Gulf sediment (Kinsman, 1966; Butler, 1970).

The poikilopic anhydrite crystals in the muddy rocks are difficult to relate to other diagenetic features. Occasionally, the pore filling crystals continued to grow into the rock replacing as they grew. The inclusion of dolomite rhombs within the margins of crystals (also noted by Peazel, 1980) indicates that anhydrite precipitation postdated at least some dolomitization. The "dirty" margins of anhydrite crystals may reflect a difference in growth rate, the dirty portion resulting from a more rapid growth rate. Alternatively, the anhydrite may have nucleated in a void and continued to grow into the rock. Celestite occurrence is rare compared to anhydrite. It replaces and thus postdates the poikilopic anhydrite. Schmidt (1965) noted that celestite had replaced anhydrite in the Upper Jurassic, Gigas Beds of Germany and considered aragonite to be the source of strontium in celestite. If aragonite is the source of strontium for Smackover celestite the
strontium could be released due to dolomitization of aragonite or from aragonite to calcite inversion of the limestones. This subject is considered further in the section entitled "Diagenetic History".

Most pyrite occurs around anhydrite nodules, particularly the ones which have been significantly reduced (compacted) in size. Pyrite crystals vary in size, may be disseminated in rock, rarely grow within the anhydrite but commonly occur as dark splotches around anhydrite nodules (Figure 11 c.).

Sulfides and Sulfates in the Upper Smackover Member:
Anhydrite nodules in the upper Smackover are rare and do not possess the black splotchy pattern common to nodules in the lower member. Nodules were observed only in the Jay and Blackjack Creek Field wells and are restricted mainly to the muddier layers of the uppermost Smackover. In the uppermost Smackover in both Jay wells (Plates IV and V) nodules coalesce to form layers (1 foot thick) of nodular mosaic anhydrite. Nodular growth was so pervasive in the uppermost Smackover muddy sediments that they also formed in the grainstone. Poikilotopic anhydrite (Figure 16 b) is surprisingly rare in the upper Smackover considering all of the pore space available in the grainstones. In contrast, the uppermost Smackover moldic grainstones and packstones are highly cemented by poikilotopic anhydrite. The occurrence of both poikilotopic anhydrite and nodular anhydrite seems to increase together. It can not be determined how much poikilotopic anhydrite is early or late (see Diagenetic History - Late Diagenesis).

In the uppermost Smackover a moderate amount of replacement celestite is present and it replaces anhydrite nodules and large
anhydrite crystals alike (Figure 23 b). Replacement invariably progresses from the anhydrite crystal periphery inward with initial replacement along intercrystalline boundaries.

Minor amounts of pyrite are associated with all sulfates. It may form disseminated, euhedral crystals or amorphous masses. Pyrite throughout the section is probably related to sulfate reduction which could have been early (Irwin and Curtis, 1977), late (Hdydari and Moore, 1989), or both.

Throughout the upper Smackover pellet wackestone facies anhydrite is present primarily as discoid and dovetail shaped anhydrite pseudomorphs after gypsum (Figure 23) similar to those described in other areas (Masson, 1955; Murray, 1960; Kinsman, 1969; Butler, 1969; McKenzie and others, 1980) as well as the Smackover (Moore and Druckman, 1981; Stamatedes, 1982). Anhydrite also occurs as pseudomorphs of mollusc shells but it is not known whether the anhydrite is a replacement or void fill. Approximately half of the sulfate observed in this facies is celestite. Inclusions of anhydrite are usually found within celestite (Figure 23 b) indicating anhydrite replacement by celestite. Calcite is also pseudomorphous after gypsum as equant, blocky, lath shaped patches (Figure 23 a). Commonly calcite incompletely replaces anhydrite and celestite. In southern Mississippi, similar calcitization was determined to the product of thermochemical sulfate reduction (Heydari and Moore, 1989). Anhydrite as displacive nodules is rare in this facies. Trace amounts of pyrite are usually associated with anhydrite and celestite as euhedral crystals or finely disseminated crystals.
Figure 23.

Upper Smackover evaporites

a. Calcite pseudomorphous after gypsum; not sure if replacement or pore fill in this case but calcite in other rocks incompletely replaces anhydrite and celestite.

b. Anhydrite (dark center, probably originally as a gypsum lath) grew into adjacent dolomite (partially replacing) and later was replaced by celestite (bright periphery). Anhydrite inclusions in dolomite and celestite are in optical continuity with center.
The presence of post burial celestite may be an indication of an aragonite precursor sediment. Higher Sr content of recrystallized south Arkansas ooids was considered to be an indication of originally aragonite versus calcite ooids (Moore and others, 1986; Swirydczuk, 1988).

Buckner Member: By far the most extensive development of nodular mosaic anhydrite occurs in the Buckner Member. Beds may be up to 20 feet thick. The nodular mosaic anhydrite is an early diagenetic product as described in the section on "Depositional Environments - Buckner Member" and by Badon (1973) or a primary subaqueous precipitate as described by Warren (1982) Warren and Kendall (1985) and Mann (1988). Subaqueous calcium sulfate formation is suggested by the abundant monocrystalline and polycrystalline anhydrite detritus associated with fine sand and silt layers. The transported sulfate may have been eroded from selenite domes like those described by Hardie and Eugster (1971) then deposited and reworked in evaporite ponds.

Poikilotopic anhydrite is most abundant in the dolomites as a pore filling cement. However, it occurs in the massive, nodular mosaic and laminated anhydrite as randomly scattered orthorhombic enhedral crystals. Crystals may also concentrate along layers (1-2 cm. thick) as if recrystallized by the compaction processes.

The minor amounts of pyrite scattered throughout the Buckner are more abundant along detrital layers. This pyrite may be related to the decomposition of plant particles or related to the presence of iron in the detrital material (Moore, 1985). The disseminated pyrite may be related to localized sulfate reduction
(Irwin and Curtis, 1977) or deep burial thermo-chemical reactions (Heydari and Moore, 1989).

**Late Calcite Cement**

Late Calcite Cement in the Lower Smackover Member: Calcite occurs as large crystals which may totally fill pores in a poikilotopic manner. Although it may share the same pore with dolomite, anhydrite, celestite and fluorite, it clearly postdates all cements. As with the other cements, the volume of calc spar is low due to the muddy nature of the sediments and porosity occlusion by earlier cements. All of the calc spar is ferroan; and where large crystals exist, the calc spars are zoned with some zones more ferroan than others. Potassium ferricyanide staining (Dickson, 1966) produces a light blue to deep purple stain in plain light.

Late Calcite Cement in the Upper Smackover Member: Minor amounts of late, coarsely crystalline calcite, occurs as void fill and replacement of anhydrite and celestite. The poikilotopic calcite in the grainstones fills voids and replaces sulfate without affecting the dolomite. This late calcite is not ferroan and therefore shows no zonation. As in the lower member, the pore-filling calc spar postdates saddle dolomite, sulfates and fluorite.

Poikilotopic calcite cement similar in morphology and paragenesis was described elsewhere in the Smackover trend (Badon, 1973; Leiker, 1977; Wagner, 1978; Dickson and Coleman, 1980; Feazel, 1980; Croft, 1980; Moore and Druckman, 1981; Brock and Moore, 1981; Stamatedes, 1982; Moore, 1985; Heydari and Moore, 1989). In south Arkansas, chemical, two phase fluid inclusion and hydrocarbon fluorescence (under ultra violet light) information indicates
elevated temperatures of formation and an intimate relation with hydrocarbon generation (Klosterman, 1980; Moore and Druckman, 1981; O'Hearn, 1985). Moore (1985) was able to show (with staining techniques combined with oxygen and carbon isotopic analysis) how the large zoned crystals grew over a period of time (and burial) as the pore fluids evolved. Further analysis by Moore (1985) showed chemical and trace element variation across these zones. Not all poikilotopic Smackover calcites are zoned. Two phase fluid inclusion data was used to further segregate the timing of zoned mosaic (42°-67°C temperature of formation) and poikilotopic calcite cement (84°C = minimum temperature of formation). These cements pre-dated hydrocarbon migration (Moore, 1985). In Mississippi, Heydari and Moore (1989) describe two periods of deep burial calcite precipitation, one before, the other after hydrocarbon migration. Oxygen and carbon isotopic analysis show the pre-hydrocarbon calcite precipitation was followed by saddle dolomite formation and post-hydrocarbon calcite precipitation occurred during thermal degradation of hydrocarbons and thermochemical sulfate reduction at temperatures in excess of 150°C.

Calcite Cement in the Buckner Member: Calcite occurs in the Buckner in two forms: as poikilotopic crystals which replaced anhydrite and as nodules (1 mm. diameter) which replaced microcrystalline anhydrite. The poikilotopic calcite is volumetrically minor compared to poikilotopic anhydrite. Inclusions of anhydrite crystallites all of unit extinction within the void filling calcite cement demonstrates a post-poikilitic anhydrite
timing. Calcite, as in the rest of the section, is the latest precipitate.

The anhedral calcite nodules are rare and were observed only in the laminated anhydrite (Figure 18 a). They replace microcrystalline anhydrite, grow around detrital quartz grains and postdate compaction and poikilitopic anhydrite precipitation. The calcite could have formed as a by-product of thermal sulfate reduction (Berner, 1971; Heydari and Moore, 1989).

Calcite replacement of anhydrite in the Jay area is common throughout the section. The calcite may take the form of 10 to 40 µm equant crystals or single larger poikilitopic crystals. The volume of calcite is low because replacement rarely goes to completion. Calcite replaces the nodular and poikilitopic anhydrites and celestite. It is clear, therefore, that calcite precipitation postdates the other late cements (saddle dolomite, poikilitopic anhydrite and celestite). This is not to say that two phases of sparry calcite precipitation as described in south Arakasas (Moore, 1985) and in Mississippi (Moore and Heydari, 1989) did not occur in the Jay area also. Many thin sections were searched to find a few concrete examples of the calcite saddle dolomite relationship which at this point can only be improved upon by oxygen and carbon isotopic data.

Calcitization of dolomite is very minor but where present it generally replaces dolomite along cleavage planes and in the centers of dolomite crystals. Calcitization of dolomite is generally considered to be a near-surface process (deGroot, 1967; Katz, 1971) under conditions compatible with low Mg^{++}/Ca^{++}, low partial pressure CO₂ and low temperatures (less than 50°C, i.e. less than 3000 feet;
deGroot, 1967). In the upper Smackover, these conditions under the influence of meteoric waters can only be met before the Buckner was deposited. Once buried the Smackover carbonates were effectively cut off from later meteoric influence by thick impermeable Buckner evaporites. However, calcitization of dolomite is more common in south Arkansas Smackover (Stamatedes, 1982) and is considered to be the consequence of long exposure to CaCl brines under deep burial condition (Land, 1985; Moore, 1985).

In the south Arkansas Smackover, Stamatedes (1982) had two cases of calcified dolomite, one in the northern zone and one in the southern zone. The northern zone calcified dolomite was considered an early product related to meteoric diagenesis, consistent with the idea of deGroot (1967). The southern zone dedolomite was considered to be related to pressure solution and deep burial zoned calcite cements. The volumetrically insignificant Jay area calcified dolomite could have formed early or late.

**Fluorite**

Minor amounts of fluorite occur as pore filling cement and as a replacement of sulfate minerals. Euhedral crystals of fluorite line the walls of vugs which demonstrates a pore filling habit. More commonly fluorite appears to fill voids but abundant, dissiminated dolomite and calcite crystals within the fluorite indicate that some fluorite replacement of carbonate occurred. Commonly, numerous small corroded remnants of anhydrite, all of unit extinction, are scattered within the fluorite, thus documenting fluorite replacement of anhydrite. Fluorite may be anhedral or pseudomorphous after gypsum and anhydrite. Fluorite surrounds saddle dolomite which is attached
to pore walls. Microstylolites were noted to extend inward from the fluorite crystal periphery. Fluorite therefore, postdates the massive microcrystalline dolomite, anhydrite and saddle dolomite. In the Humble Shell well, fluorite was found to be pseudomorphous after gypsum taking the form of discs. Scattered crystallites of anhydrite all of unit extinction with fluorite requires the sequence to be discoid gypsum replaced by anhydrite and then fluorite. Late ferroan calcite occurs in pores where fluorite lines the walls of vugs; thus, this late calcite postdates fluorite precipitation.

Fluorite in the Smackover is not very significant due to its low volume. Aragonite may be the source (up to 1600 ppm F; Carpenter, 1969) and is thought to be the source of fluorite in carbonates associated with supratidal dolomitization (Moore and others, 1972).

Silica

Silica in the Lower Smackover Member: Silica diagenesis is extremely rare in the lower Smackover and occurs only as overgrowths on detrital quartz silt. Monocrystalline, euhedral, epitaxial overgrowths replace adjacent carbonate as they grow. The detrital quartz grain nucleus is commonly recognizable. The time of this event is undetermined but it may be coincident with silicification in the upper Smackover. Similar overgrowths were recognized in this area by Feazel (1980) and in south Arkansas by Croft (1980).

Silica in the Upper Smackover Member: The only silica diagenesis noted in the Upper Smackover was that associated with clusters of sponge spicules. The quartz reprecipitated as GMC chert in nodules up to 5 cm. in diameter with pyrite, clear fluorite, amber
sphalerite, anhydrite, brown calcite and opaque light brown amorphous material. Spicules are frequently recognizable within nodules. Pyrobitumin and molds of leached dolomite crystals which are occasionally infilled with chert also occur within silica nodules. The solubility of silica increases with increasing alkalinity, high pH and reducing conditions (Correns, 1950). Similar minerologic associations are referred to by Radke and Mathis (1980) as being keyed to sulfate reduction under the influence of hydrocarbon maturation. Sulfate reduction may be biogenic (Irwin and Curtis, 1977) or thermochemical as in the reaction proposed by Barton (1967). The mineral associations with spicules suggests that biogenic silica is a catalyst to silica nodule formation in the Smackover. Dolomite precipitated as a result of the above reaction is presumed minor in occurrence because of the scarcity of silica nodules.

**Cathodoluminescence**

Cathodoluminescence (CL) microscopy in carbonates is generally used in two ways: (1) crystal zonation stratigraphy and (2) geochemical interpretations of trace element content (in conjunction with electron probe data) and redox potential of precipitating fluids (Machel, 1985; Hemming and others, 1989). In this study, applications are limited because of the finely crystalline nature of the majority of the Smackover rocks. Coarsely crystalline calcite cement (the usual target of CL studies) is volumetrically minor and irrelevant to the major dolomitization events. The descriptions which follow are visual and serve for qualitative purposes only.
Lower Smackover Member: A Nuclide Corporation Luminoscope model ELM-2B was used with a focused beam to observe polished, half unstained thin sections under a Leitz photomicroscope. The lower member dolomites are generally too finely crystalline (average a few microns in diameter) to permit optical observation of growth zonations. In effect, the microcrystalline matrix produces a cumulative dull red luminescence. Rare patches of more coarsely crystalline dolomite (up to 50 μm in diameter) occur associated with the leached intervals. These coarser crystals commonly show three to five zones of alternating bright and dull red-orange luminescence. Saddle dolomite luminesces the same color but not as brightly. They are typically a homogeneous dull red-orange, though a number of zoned saddle dolomite crystals possess a narrow quenched zone. Poikilotopic calcite consistently produces a bright yellow luminescence which commonly shows zonation. As many as seven zones were observed of alternating bright yellow and totally quenched zones.

The ubiquitous luminescence of the lower member dolomites indicates that they probably contain concentrations of at least 100 ppm Mn$^{++}$ and less than 10,000 ppm Fe$^{++}$ (Pierson, 1981). The zoning in some dolomite crystals indicates their formation under conditions of fluctuating ferrous iron availability during precipitation.

Upper and Uppermost Smackover: The upper Smackover dolomites invariably exhibit a homogeneous moderately bright red-orange luminescence. The luminescent properties indicate Mn$^{++}$ and Fe$^{++}$ concentrations equal to those described for the lower member dolomites. The lack of crystal growth zonation indicates the upper
member dolomites precipitated from a solution which maintained a constant composition relative to Mn$^{++}$ and Fe$^{++}$.

The uppermost Smackover dolomites are generally finely crystalline and exhibit luminescent characteristics similar to those of the lower member microcrystalline dolomites. The few coarsely crystalline intervals have dolomites with uniform luminescence similar to upper Smackover dolomite behavior.

Buckner Member: The cathodoluminescent characteristics of the Buckner dolomites are similar to those of the upper and uppermost Smackover with the exception of the dolomite crystals disseminated within massive bedded anhydrite. These crystals vary in size (up to 40 $\mu$m), luminesce bright red-orange and have as many as seven distinct zones.

**Two-Phase Fluid Inclusions**

Two phase fluid inclusions were visible only in the coarsely crystalline upper Smackover dolomites. They are ubiquitous and measure approximately 4 $\mu$m in diameter which is too small for reliable measurement of homogenization and freezing temperature determinations (Klosterman, 1982). If the inclusions are primary it would indicate the dolomites formed at temperatures higher than surface temperatures, or that they may have recrystallized at depth. On the other hand, the inclusions could be secondary forming along pressure induced cleavage or twin imperfections. The most common cause of reequilibration is hydrofracturing: cracking the crystal from fluid inclusion over pressure, fluid composition equilization with pore fluid and healing of the crack (Goldstein, 1986).

Goldstein described how wells studied, Mississippian age fresh water
Cements in the Sacramento Mountains of New Mexico had not recrystallized (based upon petrographic and geochemical data) but had reequilibrated (based on two-phase fluid inclusions) with higher salinity and higher temperature fluids. In deeply buried rocks, some inclusions hydrofracture repeatedly, and others, not at all. The result is a data population with a wide range of variability which, in certain cases, may still be interpretable.

Two-phase fluid inclusions in the Smackover have been evaluated with varying degrees of success (Klosterman, 1981; Moore, 1985; O'Hearn, 1985). O'Hearn found his data to segregate in a depth-salinity relationship according to crystal origins (early bladed cement, poikilotopic calcite, saddle dolomite, etc.) Moore (1985) was able to distinguish differences in the temperature of formation of zoned mosaic and poikilitic calcite cement, and allowed for comparisons with $^{18}O$ paleo-temperatures. These studies, however, are of rocks buried 7,000 to 10,000 feet. The Jay area upper Smackover dolomites are buried over 15,000 feet, thus run greater risk of hydrofracturing (Goldstein, 1986). The upper Smackover dolomites are either a product of deep burial precipitation (or recrystallization) prior to saddle dolomite precipitation or the only inclusions noticed (two-phase) were the ones which hydrofractured as a result of burial. Epigenetic bladed calcite cements (noted on Page 44) also possess two-phase fluid inclusions which must be the result of hydrofracturing (according to Goldstein, 1986). In south Arkansas, similar inclusion rich, bladed cements associated with moldic porosity were described from the northern meteoric diagenetic zone (Moore and Druckman, 1981).
Chemistry

Whole rock chemical analysis performed on carbonate rocks (Allan and Mathews, 1977; Margaritz and others, 1979) is becoming increasingly obsolete. Chemical analyses of limestones today are performed not only on individual bioclasts, ooids, cements and various other isolated components (Stamatedes, 1982; O'Hearn, 1985; Moore and others, 1988) but also on solitary crystals (Reeder and Wenk, 1979; Heydari and Moore, 1989) or even growth zones within crystals (Dickson and Coleman, 1980; Moore, 1985; Ward and Halley, 1985). Dolomitization, however, is commonly believed to be a dissolution-reprecipitation reaction (Folk, 1965; Bathurst, 1971; Hudson, 1977; Gaines, 1980; Land, 1980) which tends to homogenize rock composition. The Buckner, upper Smackover and to a certain extent the lower Smackover sediments were dolomitized to a homogeneous crystalline texture. Therefore, it is practical in this case to do whole rock chemical analysis on the dolomite portions as long as one is convinced that the dolomitization event was a single diagenetic event. Dolomites from the Jay area were concentrated by treatment for the removal of calcium sulfates and calcite before analysis (see Appendix A).

The preceding petrographic and stratigraphic observations revealed four types of dolomite in the Jay Field area: Buckner and Buckner related dolomite, upper Smackover dolomite, lower Smackover dolomite and saddle (baroque) dolomite. A total of 103 dolomite samples (40 = lower Smackover; 56 = upper Smackover; 7 = Buckner) were separately analyzed for their $\text{Mg}^{++}$, $\text{Ca}^{++}$, $\text{Sr}^{++}$ and $\text{Na}^{+}$ cation concentrations. The crystallography of the dolomites was examined by
x-ray diffraction techniques to further characterize the different types.

Oxygen and carbon stable isotope determinations were made on seventy-one samples of the four dolomite types. The intent is that these chemical data when combined with the stratigraphy and petrography will give insight as to the fluids and mechanisms responsible for dolomitization. The data are tabulated and the analytical methods are discussed in detail in the Appendices.

Presentation of Dolomite Chemistry Data

The two most meaningful ways to present the Smackover chemical data is in cross-plots for comparison to other studies and in a composite vertical sequence so that the reader may visualize changes in chemistry as it relates to changes in lithology and stratigraphy. Many authors have used this second method effectively (Supko, 1977; Choquette and Steinen, 1980; Lumsden and Chimahusky, 1980; Sass and Katz, 1982).

Figures 24 - 29 present all chemical data acquired for each well. The gross lithology (limestone, dolomite, anhydrite) is provided and a range in crystal size is given to demonstrate the degree of variability. Crystal size variation roughly correlates with changes in chemistry. Trace elements are reported in parts per million (ppm) and as molar ratios relative to calcium. Molar percent excess Ca^{++} is given by both x-ray diffraction (XRD) and atomic absorption spectrophotometry (AAS) analysis for comparison. The two results show good agreement, usually within one mole percent.
Figure 24.

Chemistry of Humble #1 Shell 20-1. At 15620, note the change in crystal size and dramatic change in oxygen isotopic composition. Other observations are the high excess Ca++ in the lower Smackover dolomites and higher Sr and Na content of samples above 15620 (also see Figure 40 and Plate IV for upper Smackover detail).
Figure 25.

Chemistry of Exxon #1 Swift 10-5. Note the change in crystal size and oxygen isotopic composition at 15440. Also notice the high Sr and Na composition above 15440, as well as the high Na and $\text{SiO}_2$ from 15530 to 15630. (see Figure 41 and Plate V for greater detail).
Figure 26.

Chemistry of Exxon #15 W. St. Regis. Note the crystal size change six feet below the top of the Smackover and also the corresponding changes in trace element and oxygen isotopic compositions (also compare Figure 42 to Plate VI for greater detail).
Figure 27.

Chemistry of Exxon #1 McCurdy 12-1. Buckner was not cored which prevent recognition of uppermost Smackover. Upper Smackover dolomites are similar to those of Jay Field in every respect.
Figure 28.

Chemistry of Exxon #1 Hart 26-3. Upper Smackover dolomite is sparse (see Plate III); however, Smackover dolomites are calcian and finer crystalline compared to upper Smackover.
Figure 29.

Chemistry of Chevron #1 Scott.
X-Ray Diffraction Analysis of Dolomites

X-ray diffraction (XRD) techniques were used to determine the Mg/Ca of the dolomites (after Katz, 1971) as a quality control to check the Mg/Ca values obtained by atomic absorption spectroscopy. Quantitative discussion concerning the variations in mole percent excess calcium are reserved for the section entitled Dolomite Stoichiometry.

There were noticeable differences among the petrographically distinguished dolomite types concerning the shape of their diffractogram (116) peaks. The coarsely crystalline upper Smackover dolomites consistently produced peaks of strong intensity (Figure 30) whereas the finer crystalline Buckner and lower Smackover dolomites produced lower intensity, diffuse peaks in the back reflection region (50°-52° 2θ). In all cases the analytical parameters were equal. The diffuse peaks are occasionally asymmetrical, tailing off toward the higher 2θ direction. The diffuse-asymmetric behavior is reported to be common to reflections which have strong c-axis components, whereas sharp peaks have reflections with strong a-axis components (Goldsmith and Graf, 1958a). Alternatively, diffuse peaks may represent a wider range of composition (Goldsmith and Graf, 1958b). The peak shapes of the Smackover and Buckner dolomites correspond well to excess Ca⁺⁺, the sharp peaks being characteristic of more stoichiometric dolomites. As the amount of excess Ca⁺⁺ increases the shape of the curve becomes increasingly rounded which indicates increased compositional variation. All of the Smackover and Buckner dolomites possess the principal order reflections (Graf and Goldsmith, 1956).
Figure 30.

Diffractogram trace (116, 108 peaks) of typical upper Smackover (ESw 15440) and lower Smackover (ESw 15698) dolomites. Upper Smackover dolomites are well crystalline, stoichiometric and coarse (up to 350 um). Lower Smackover dolomites are poorly crystalline (broad, low peaks) calcian and aphanocrystalline.
Dolomite Cation Concentrations

Dolomite Stoichiometry: Ideal dolomite refers to a dolomite with a molar Mg/Ca of 1:1. The dolomites in this study vary from ideal to calcic \((\text{Ca}_{0.60} \text{Mg}_{0.40} \text{CO}_3)\). The amount of excess \(\text{Ca}^{++}\) or degree of nonstoichiometry was determined by both AAS analysis and XRD techniques (see Appendix). Error in the Mg/Ca by AAS analysis could arise from \(\text{Ca}^{++}\) contamination from anhydrite and/or calcite. With the exception of HS-680, 696, 705, 710 and 714, \(\text{Ca}^{++}\) contamination was negligible. The XRD technique used (Katz, 1971) involved noting a change in d-spacing by measuring the (116) peak position. Excess \(\text{Ca}^{++}\) in dolomite increases the d-spacing of the lattice planes and causes the x-ray diffraction peaks to shift to a higher 2θ value (Goldsmith and Graf, 1958a). In this study, a shift of the (116) peak position was measured relative to the (220) peak of a fluorite internal standard. Error in the Mg/Ca determined by XRD may also arise from substitution by other ions (\(\text{Fe}^{++}\), \(\text{Mn}^{++}\)) which could cause a similar peak shift but this should be a factor only with the saddle dolomites. Cathodoluminescence observations show all the Smackover and Buckner dolomites in the area to luminesce moderate to dull red-orange. Therefore, \(\text{Fe}^{++}\) is suspected to be near 1500 ppm and \(\text{Mn}^{++}\) 100 ppm (Pierson, 1981). This \(\text{Fe}^{++}\) concentration is far less than the 3 mole % required to cause a detectable peak shift (Goldsmith and Graf, 1958a). Additionally, with the exception of saddle dolomite, the dolomites fail to stain blue with potassium ferricyanide (Dickson, 1966) indicating less than 1 mole % \(\text{FeCO}_3\).

All Holocene and Pleistocene dolomites analyzed to date are poorly ordered and calcian. Evaporative dolomites (Muller and Tilty,
1966; Bubb and Atwood, 1968; Katz, 1971; Behrens and Land, 1972; Cook, 1973; Kinsman and Patterson, 1973; Aharon and others, 1977) can be as calcian as suspected mixed water dolomites (Land, 1973a; Gebelein and others, 1980; Ward and Halley, 1985). Although Katz (1971), Sass and Katz (1982) and Sass and Bein (1988) considered that the Mg/Ca of dolomite depends on the Mg/Ca of the precipitating solution whereby excess Ca$^{++}$ in dolomite decreases with increasing Mg/Ca in the water, it is debatable whether solutions of low salinities but high Mg/Ca could have the same effect (Folk and Land, 1975). There is no apparent correlation in ancient dolomites between the amount of excess Ca$^{++}$ and either insoluble residue, porosity, rock type, calcite-dolomite ratio or crystal size (Lumsden and Chimahusky, 1980; Sass and Katz, 1982). However, there is an apparent correlation between the stoichiometry of ancient dolomites and salinity (Sass and Bein, 1988; discussion to follow). Another common view is that stoichrometric dolomites may be produced by progressive recrystallization during burial (Land, 1980; Hardie, 1987).

While the amount of excess Ca$^{++}$ in the Jay area dolomites does not seem to be indicative of an environment of dolomitization, a vertical display of each well (Figures 24-29) allows for some stratigraphic based comparisons. The lower Smackover, Buckner and uppermost Smackover are more calcian than the upper Smackover dolomites, which are nearly ideal. The 1-5 mole % excess Ca$^{++}$ range for Buckner dolomites is similar to that of dolomites (Kinsman and Patterson, 1973) from Persian Gulf sabkhas. The upper Smackover dolomites average 1.6 mole % excess Ca$^{++}$ with 4 samples of ideal
dolomite. The lower Smackover dolomites are the most calcian averaging 5.0 mole % excess Ca$^{++}$. Three samples in the Chevron Scott and two in the Humble Shell analyzed 9.5 mole % excess Ca$^{++}$ (Figures 24 and 29) by XRD and AA analysis.

Katz (1971) and Sass and Bein (1988) predicted that precipitating dolomites progress from calcian to more stoichiometric as salinity increases from 2-3 times sea water concentration to past the range of gypsum and anhydrite precipitation with a concomitant increase (in the dolomite) in sodium content. At high salinities beyond halite precipitation, Mg/Ca continues to increase producing nearly stoichiometric dolomite. As halite precipitates, the resulting decrease in Na/Ca results in associated dolomites with low sodium content.

Following the logic of Katz (1971) and Sass and Bein (1988), the lower Smackover dolomites may represent precipitation from slightly evaporated brines with a fairly constant Mg/Ca of 15-20. The high density of nucleation sites created the aphanocrystalline texture and what amounts to a mass of calcian dolomite crystal centers. The Buckner dolomites which are less calcian probably precipitated from more concentrated brines with Mg/Ca of 25-35. The upper Smackover dolomites are the most ideal and, following Katz (1971) and Sass and Bein (1988), may represent precipitation from past halite (waters after they have produced considerable halite), high salinity brines with Mg/Ca=35. Alternatively, the stoichiometric upper Smackover dolomites may be a product of low salinities (Folk and Land, 1975). Ideal limpid dolomites are suspected to form in brackish solutions with Mg/Ca as
low as 1:1 (Folk and Land, 1975), but dolomite documented to be of this origin is scarce. This subject is pursued in detail in the Dolomitization section.

Trace elements: The relationship used to relate cation concentrations in solids to the liquids from which they precipitated is given by: $(m_i/m_{\text{Ca}^{++}})_{\text{solid}} = D_i (m_i/m_{\text{Ca}^{++}})_{\text{liquid}}$ where $m_i/m_{\text{Ca}^{++}}$ is the molar ratio of a particular ion with Ca$^{++}$ and $D_i$ is a distribution function or partition coefficient of the ion of interest. With respect to carbonates, it is hypothesized that the Sr and Na content of calcite and dolomite reflect the Sr/Ca and Na/Ca of the solutions from which they precipitated. From the literature, however, the interpretation of trace elements in dolomites is ambiguous. Land (1980) has pointed out the state of confusion regarding Sr$^{++}$ and Na$^+$, and his arguments will not be repeated here. One of the problems is the inability to determine (experimentally) partition coefficients for trace elements in dolomites under earth surface conditions (low temperatures and pressures). The problem is greatly compounded when dealing with burial conditions. Holocene and Pleistocene "protodolomites" apparently have a similar range in Sr$^{++}$ values regardless of whether they precipitated from brines (Sr$^{++} = 400-1000$ ppm) (Behrens and Land, 1972; Cook, 1973; Land and Hoops, 1973) or brackish water (dolomite Sr$^{++} = 65-3000$ ppm) (Land, 1973a, b; Supko, 1977). A wide range in Sr (100-1300 ppm) was shown to exist even in dolomites formed in deep ocean sediments where conditions (temperature, salinity, etc.), one might think, are expected to fluctuate the least (Baker and Burns, 1985). The same situation applies to Na$^+$ for which there are no proposed partition
coefficients (Sass and Bein, 1988). Na⁺ concentration can be masked by contamination from fluid and solid inclusions in the sample, clay minerals, laboratory glassware, and intercrystalline salts from formation fluids. Generally speaking, ancient dolomites appear somewhat depleted in Sr²⁺ and Na⁺ relative to Holocene analogs, for reasons which are poorly understood but probably related to protodolomite stabilization. Qualitative comparisons, however, are still useful because relative differences can be preserved (Fritz, 1971; Hanford and Moore, 1976; Land, 1980; Sass and Katz, 1982; Moore and others, 1988; Sass and Bein, 1988).

**Strontium:** The Buckner and uppermost Smackover dolomites have Sr²⁺ values ranging from 103-334 ppm with an average of 202 ppm, which is similar to the lower range for dolomites of Holocene sabkhas. The low Buckner values are not unique. Ancient dolomites, relatively close in age, which are interbedded with anhydrites of comparable origin are similar in δ¹⁸O and Sr²⁺ composition to the Buckner dolomites (Figure 31). The Danish Zechstein sabkha dolomites of Permian age have an average Sr²⁺ of 272 ppm (Clark, 1980) and the Lower Cretaceous evaporite related dolomites of Tunisia (M'Rabet, 1981) average 104 ppm. Other ancient dolomites in outcrop (Rudolph, 1978; Mattes and Mountjoy, 1980; Dunham and Olson, 1980; N. E. England Zechstein of Clark, 1980; Sass and Katz, 1982) are ignored here because reequilibration with Tertiary ground water systems can be argued.

Low Sr²⁺ in ancient dolomites is currently explained in one of three ways. Either the dolomites precipitated from fresh waters (Land, 1980), which is unlikely for dolomites with sabkha
Figure 31.

Strontium versus $\delta^{18}O$ of the Buckner and uppermost Smackover dolomites compared to other ancient sabkha dolomites. Simply shows similarity in ranges.
Permian.............. Clark (1980)
Lower Cretaceous..... M’Rabet (1981)
Jurassic............. (this study)
stratigraphy; Sr\textsuperscript{++} partitioning is controlled by a low partition coefficient (best D for Buckner = 0.05 Katz and others, 1972; Morrow and Mayers, 1978; Sass and Starinsky, 1979; Baker and Burns, 1985) or recrystallization by low Sr/Ca waters (Land, 1980) at elevated temperatures during burial. Recrystallization of Jay area dolomites does not seem feasible unless it can occur without destroying the \$^{18}O$ content, the crystal zoning (observed by cathodoluminescence) and the radiometric Sr signature yet to be discussed. There is some indication that Sr\textsuperscript{++} partitioning in calcite is only slightly effected by temperature and salinity (Katz and others, 1972) but other factors difficult to monitor may strongly effect Sr\textsuperscript{++} content, such as, rate of crystal growth, the amount of Ca\textsuperscript{++} in solution (Katz and others, 1972; Baker and Burns, 1985; Moore, 1985; Machel and Anderson, 1989), and the degree of "openness" of the system (Kinsman, 1969; Land, 1973; Baker and Burns, 1985).

In order to conduct a fair test of partition coefficients one must not only know the origin of the dolomite (cement) but also have the ability to sample the pore fluids to determine their Sr/Ca. Calcite from the Smackover of southern Arkansas was used to test partition coefficients (Moore, 1985). Coarsely crystalline Smackover calcite cement was determined to be a late, deep subsurface cement by petrographic relations (Moore and Druckman, 1981; Brock and Moore, 1981; Stamatedes, 1982; Moore, 1985) oxygen isotopic analysis (Dickson and Coleman, 1980; Moore, 1985) and two phase fluid inclusion analysis (Klosterman, 1981; O'Hearn, 1985; Moore, 1985). By knowing the Sr/Ca of present south Arkansas Smackover brines (Collins, 1974) Moore (1985) was able to suggest that the Sr content
(approximately 100 ppm) of the poikilitic calcite cement was too low to be explained by a $D_{\text{Sr}}^C = 0.045$ (Katz and others, 1972). He suggested rates of precipitation may be the controlling factor in this case.

Studies of Miocene to Recent deep sea dolomites led Baker and Burns (1985) to estimate $D_{\text{Sr}}^D = 0.06$ for dolomite precipitating from seawater (Mg/Ca = 5) to slightly altered (due to dolomitization and/or calcite precipitation caused by methanogenesis) seawater (Mg/Ca = 3-4). Dolomitization within a few tens of meters below the sea bottom, plus the fine grained nature of the organic rich calcareous sediments promotes microenvironments with different pore-water Sr/Ca. The first dolomites to precipitate from normal seawater should have Sr/Ca = $5.1 \times 10^{-4}$ or about 245 ppm Sr. They state that continued dolomitization lowers the Sr/Ca which can result in a dolomite with much lower Sr (150 ppm or less). Extremely high Sr dolomite was also reported. For example, sufficient organic matter promotes sulfate reduction which increases dissolved bicarbonate and thus calcite precipitation. The resulting decrease in Ca causes higher Sr/Ca (0.017 to 0.045) pore water and high Sr content (480 - 1290 ppm) dolomite.

Strontium analysis of dolomites and brines from a Persian Gulf sabkha (Kinsman, 1966) allows partition coefficients $D_{\text{Sr}}^D_{\text{Dolo.}}$ to be tested on the Buckner dolomites also of evaporative origin. If $D_{\text{Sr}}^D$ is assumed to be the controlling factor in dolomite, and $D_{\text{Sr}}^D = 0.05$ is applied, a dolomite precipitated from sabkha brines should have Sr$^{++}$ concentrations of approximately 270 ppm. The Buckner dolomites have an average Sr$^{++}$ value of 200 ppm. South Arkansas and
east Texas Buckner dolomites have similar but slightly higher strontium values (average = 357 ppm, Stamatedes, 1982; Moore and others, 1988). It would appear that the Buckner values could be explained by using the most commonly accepted $D_{Sr}^D = 0.05 - 0.06$ (Katz and others, 1972; Morrow and Mayers, 1978; Sass and Starinsky, 1979, experimentally determined over the temperature range 40°-90°C; and Baker and Burns, 1985) and sabkha water chemistry. Although a $D_{Sr}^D = 0.05 - 0.06$ will explain values from the Buckner, other ancient evaporative dolomites and Recent seawater dolomites formed in a closed hydrologic system, it is too low to explain the Sr concentrations of Holocene evaporative dolomites (840 -970 ppm, Behrens and Land, 1972; 400 - 800 ppm, Cook 1973; 600 - 900 ppm, Land and Hoops, 1973). The answer, of course, is to understand the Holocene metastable, calcian, poorly ordered, higher Sr content dolomites (or protodolomites) and their thermodynamic drive for increased ordering (Hardie, 1987). The problem is not of one variable but of multiple factors (other mineral precipitation and dissolution, organic reactions, fluid flux, kinetic effects, etc.) which operate simultaneously (Moore, 1985; Sass and Bein, 1988).

Worthy of note is that some of the Buckner samples analyzed are of dolomites encased in impermeable anhydrite, seemingly protected from post-depositional fluids. The subject of deep burial recrystallization is addressed further in the subsequent discussion on the upper Smackover chemical discontinuity.

The upper Smackover dolomites in the Jay area average approximately 73 ppm Sr. The $D_{Sr}^D$ of 0.05 - 0.06 favored for the Buckner dolomites is in agreement with Sr of upper Smackover
dolomites if dolomitized by mixed marine-meteoric waters. The narrow range of the upper Smackover Sr (51 - 95 ppm) and the porous, oomoldic nature of the rock suggests dolomitization in an open, free flowing hydrologic system. Pleistocene dolomites suspected to have formed by mixed waters (Sr$^{++}$ = 65-3500 ppm; Land, 1973 a, b; Supko, 1977) can be explained with $D_{Sr} = 0.06$ if the sediments were aragonite (Sr = 9000 ppm) and of low permeability to promote the development of extreme microenvironments. Using the above partition coefficient, upper Smackover dolomites are apparently not in equilibrium with present Smackover brines (Table B-6 in Appendix B) which have considerably higher Sr/Ca (0.034, Table B-6, Appendix B) than sabkha brines of today or normal seawater. A dolomite formed in normal seawater (seawater Sr/Ca = 0.0086) with a $K = 0.06$ should contain approximately 245 ppm Sr (Baker and Burns, 1985). The strontium contents of the south Arkansas (average Sr = 59 ppm, Stamatedes, 1982) and east Texas upper Smackover oomoldic dolomites (average Sr = 54 ppm, Moore and others, 1988) are similar to the Jay area oomoldic dolomites. A second group of subordinate, post compaction (grain to grain) zoned, replaced dolomite (not present in Jay area) associated with stylolites and pressure solution in south Arkansas - east Texas (Figure 32) also have similar strontium values (average Sr for Arkansas - Texas areas = 62 ppm; Stamatedes, 1982; Moore and others, 1988). The Arkansas and Texas upper Smackover oomoldic dolomites were believed to be formed in mixed meteoric - marine (Stamatedes, 1982) or mixed meteoric - evaporated marine waters (Moore and others, 1988).
Figure 32.

Sr and Na of the Jay Field area matrix dolomites (boxed in areas) compared to upper Smackover and Buckner dolomites of east Texas (modified from Moore and others, 1988). Texas Buckner dolomites are higher in Sr and Na than in Jay area. Texas upper Smackover dolomites are similar in composition to Jay area upper Smackover dolomites.
The inconsistencies in strontium concentrations of Holocene and ancient dolomites are obvious. Buckner, Smackover and other ancient dolomites in general appear slightly depleted in Sr$^{++}$. If this depletion affected the Smackover and Buckner dolomites equally, the proportional differences would likely be preserved. This relative difference should reflect the dolomitizing fluid composition. If the Buckner related dolomites formed in an evaporative environment, then the upper and lower Smackover dolomites either precipitated from solutions of lower salinity or they have recrystallized.

There are so many variables and scenarios available to explain dolomite Sr concentrations that it may be more meaningful to compare the Sr concentration of various Smackover and Buckner dolomites to each other. It would be instructive to determine if dolomitization affected original aragonite or calcite sediment. Recent workers (Sass and Katz, 1982) have used covariation of Sr$^{++}$, Mg$^{++}$, and Na$^+$ ratios with Ca$^{++}$ to distinguish dolomitization of an aragonite rather than calcite precursor in slightly evaporative seawater. A comparison of Sr/Ca to Mg/Ca in Figures 24-29 (where sufficient data permit) of the Buckner and upper Smackover dolomites shows a consistent antipathetic covariation of the Sr/Ca and Mg/Ca. This covariation trend between Sr and Mg in the Soreq dolomites of Israel (Sass and Katz, 1982) suggests dolomitization of an aragonite precursor rather than a calcite precursor in a partially isolated system. The Sr/Ca in seawater ($8.6\times10^{-3}$) is intermediate between the Sr/Ca in aragonite ($1.1\times10^{-2}$) and calcite ($3.0\times10^{-4}$). Therefore, with an aragonite host rock, as dolomitization proceeds the Mg/Ca of
the fluids should decrease while the Sr/Ca increases. The opposite relationship results if calcite is dolomitized rather than aragonite. The same relationship holds true for dolomitization in mixed water \((Sr/Ca = 3.5 \times 10^{-3}\) for mean North American river water; Skougstad and Horr, 1963) as well. This relationship assumes that the ratios in the dolomites reflect the ratios of the liquids from which they were precipitated.

The behavior of the \(Sr^{++}\) and \(Mg^{++}\) ratios with \(Ca^{++}\) in the lower Smackover dolomites is more chaotic than in the upper Smackover. This is contrary to expected behavior (after Sass and Katz, 1982) because the sediment was muddy, hence a more closed system in comparison to the porous upper Smackover grainstones. The reasons for this behavior are unclear. The Sr concentrations of the Saroque dolomites (average \(Sr^{++} = 93\) PPM) are similar to the lower Smackover dolomites (average \(Sr = 82\) PPM) as are the other chemical and petrographic characteristics yet the variations are opposite to that observed in the Saroque dolomites. While the covariation of Sr and Mg with Ca concept seems reasonable (after Sass and Katz, 1982) the results of this exercise, with respect to the Smackover, are opposite to expected behavior.

**Sodium:** While, in the literature, more attention is usually given to discussions of Sr concentrations in dolomites, Sass and Bein (1988) offer the most comprehensive discussion on factors which may affect the concentration of Na in dolomites. They state that coupled substitution of monovalent \(Na^+\) for bivalent \(Ca^{++}\) negates the possibility of a single partition coefficient. In spite of this and the problematical non-lattice sources of \(Na^+\) (discussed on Page
77) a range was predicted for $D^D_{Na}$ (Sass and Bein, 1988). They predicted $D^D_{Na}$ to range from $(1.4$ to $2.5) \times 10^{-4}$. This prediction was based on knowledge of the activity behavior of Na/Ca with ionic strength, the general range of Na/Ca in seawater brines, and the Na concentration in dolomite associated with gypsum (400-2700 ppm). They also indicated that $D^D_{Na}$ should vary with increased salinity thus changing the compaction of associated dolomites. As salinity increases to the stage of gypsum and anhydrite precipitation, both the Na/Ca in solution and $D^D_{Na}$ increase and should be reflected by an increase in sodium content in dolomites. At high salinities beyond halite precipitation the trend is reversed resulting in low Na content in dolomites associated with halite.

In Buckner and Smackover dolomites (Figures 24-29) the variation in Na$^+$ content parallels the Sr$^{++}$ variations. The Na$^+$ is highest in Buckner related dolomites (average $= 320$ ppm) averaging 100 ppm more than the upper Smackover dolomites (average $= 228$ ppm). In spite of being encased within impermeable anhydrites, the Buckner values are considerably lower than reported Na$^+$ in Recent evaporative dolomites from Baffin Bay, Texas (1,000-2,500 ppm, if indeed crystal lattice sodium) and the Persian Gulf (2,350 ppm) (Land and Hoops, 1973), but within the lower end of the predicted Na range of evaporative dolomites reported by Sass and Bein (1988). In the Smackover dolomites, the low Na content, (lower Na values than Buckner dolomites) suggest dolomitization in either high salinity (past halite) or low salinity (near seawater) fluids (Sass and Bein, 1988).
If the original Na\(^+\) content of the Buckner dolomites encased in evaporites is not preserved then it is less likely to be preserved in the porous Smackover dolomites. In any case, it is very likely that the proportions of Na in the Buckner relative to Smackover are preserved. Figures 24 - 29 show that Na/Ca concentrations vary sympathetically with Sr/Ca concentrations and antipathetically with Mg/Ca concentrations. The result parallels the Soreq dolomites (Sass and Katz, 1982). Because the Na/Ca in marine aragonites (1.5x10\(^{-2}\)) is far lower than seawater (Na/Ca = 46; Katz, 1977), the Na/Ca in dolomites is controlled by the Ca\(^{++}\) in solution, by salinity (Sass and Katz, 1982; Sass and Bein, 1988) and by unknown ion substitution factors arising from monovalent sodium substituting for divalent calcium (Sass and Bein, 1988). If salinity remains constant during dolomitization in a semi-closed system the Na/Ca should decrease as Mg/Ca decrease resulting in a sympathetic relationship. The antipathetic Na/Ca and Mg/Ca relationship indicates the dominance of salinity effects over the weaker effects on the ratios by the dissolving calcites. An increase in salinity parallels and probably perpetuates an increase in dolomitization (Sass and Katz, 1982, Sass and Bein, 1988).

**Oxygen and Carbon stable isotope data**

The isotopic fractionation of oxygen and carbon in the dolomite-H\(_2\)O-CO\(_3\) system is poorly understood due to the difficulty of dolomite synthesis under sedimentary conditions (Hudson, 1970; Land, 1980; Land, 1985). Nevertheless, oxygen and carbon stable isotopic composition of the rocks can be diagnostic of certain conditions at the time of precipitation. Comprehensive reviews on isotopes in
carbonates are provided by Hudson (1977), Irwin and others (1977), and Land (1980). All carbonate isotopic values expressed in this report are relative to the Chicago PDB standard unless stated otherwise.

The oxygen and carbon stable isotopic data for the Jay area Smackover and Buckner dolomites is presented in a standard crossplot in Figure 33 (also see Table B-4). The eighteen Buckner and uppermost Smackover dolomites associated with anhydrite layers distinctly plot well into the positive range for both oxygen and carbon, as do three samples from the Exxon Swift (middle Smackover) which are also associated with anhydrites. The upper (29 samples) and lower (22 samples) Smackover have lighter oxygen (than Buckner) but similar carbon values. The upper and lower Smackover carbon values differ by approximately 2% and seem to form two populations. The lone saddle dolomite value has similar carbon character to the others but is considerably lighter in oxygen as was the case in south Arkansas (Stamatedes, 1982). Thirty additional analyses of upper Smackover dolomites from Jay and Big Escambia Creek Field were plotted in Figure 34. The new data from recent studies (Powell, 1984, Sailer and Moore, 1986) help reinforce the patterns revealed by this study.

Buckner: The $\delta^{18}O$ values of 11 Buckner samples average $+1.5\%$ and are in the same range as those reported by McKenzie (1981) and Kinsman (1973) for the Persian Gulf sabkhas (Figure 35). Ancient sabkha dolomites with similar positive $\delta^{18}O$ values (Figure 36) have been reported from subsurface sequences (Clark, 1980) and in surface outcrops (Rudolph, 1978; M'Rabet, 1981). Normal Jurassic seawater
Figure 33.

Oxygen and carbon stable isotopic values of the Smackover and Buckner dolomites, Jay-Big Escambia Creek area (modified from Vinet 1982, 1984). The three so called "middle Smackover" dolomites from the Exxon Swift are actually upper Smackover but have chemistry and stratigraphy similar to Buckner and uppermost Smackover as discussed on Page 106.
- Buckner Dolomite (11)
- Uppermost Smackover (7)
- Upper Smackover (32)
- Lower Smackover (20)
- Saddle Dolomite (1)
- Middle Smackover, Exxon Swift
Figure 34.

Smackover and Buckner oxygen and carbon isotopic data supplemented with the additional, data from Powell (1984) and Sailer and Moore (1986). The data from Powell (twenty analyses) is from two Jay Field wells: Humble Braxton 21-1 and the Humble Moncrief 10-2 (also see Figures 43 and 44) The data from Sailer and Moore (ten analyses) is from the western part of Big Escambia Creek Field. The three unmarked fields are from Figure 33.
- Buckner Dolomite
- Uppermost Smackover Dolomite
- Upper Smackover Dolomite
- Upper Smackover Dolomite

Jay Field (Powell, 1984)

Big Escambia Creek (Saller & Moore, 1986)
Figure 35.

Smackover and Buckner dolomites compared to Recent dolomites of evaporative origin. The Buckner dolomites compare favorably with the Baffin Bay and Persian Gulf dolomites with respect to both oxygen and carbon. The three unmarked fields are from Figure 33.
Figure 36.

Smackover and Buckner dolomites compared to other ancient dolomites. The Buckner dolomites match well with those of Clark (1980) and Rudolph (1978). Three unmarked fields are from Figure 33.
Saddle Dolomite
south Arkansas
Stamatedes'82

S\(^{18}\)O

S\(^{13}\)C

Clark'80

Rudolph'78

M'Rabet '80

Sass& Katz'82
oxygen isotopic composition is estimated to be approximately -1.2 to -1.5\%\textsubscript{o}(Irwin and others, 1977; Lohmann, 1988). If there is a 3\%\textsubscript{o} fractionation factor, one would expect a normal salinity marine Smackover dolomite to have a composition of approximately +1.5\%\textsubscript{o}. Buckner dolomites, seemed to have formed in evaporated seawater and average +1.5\%\textsubscript{o} in \textsuperscript{8}\textsuperscript{18}O. Therefore, according to Buckner values, the upper Smackover dolomite \textsuperscript{8}\textsuperscript{18}O should be -0.5\%\textsubscript{o} if formed in normal salinity Jurassic seawater. The Buckner dolomites apparently have close to their original \textsuperscript{8}\textsuperscript{18}O preserved and basically support an evaporative origin as indicated by their stratigraphy (Vinet, 1982, 1984). Buckner dolomites in south Arkansas and east Texas have similar \textsuperscript{8}\textsuperscript{18}O values (average = 0.6\%\textsubscript{o} PDB) (Stamatedes, 1982; Moore and others, 1988) (Figure 37).

The Buckner \textsuperscript{13}C values have the same range as those of the west Texas Permian in outcrop (Rudolph, 1977) and the Permian Zechstein in outcrop and subsurface (Clark, 1980) and the south Arkansas-east Texas subsurface (Stamatedes, 1982; Moore and others, 1988) all from evaporative carbonate-anhydrite sequences. Rudolph used Sholle and Arthur's (1976) idea of \textsuperscript{13}C enrichment of seawater by preferential photosynthetic fixation of \textsuperscript{12}C in basinal sediments by organisms. Clark (1980) employed fermentation of underlying sediments during dolomitization of the Zechstein. Neither mechanism can be entirely ruled out for the Smackover. Selective photosynthetic fixation of light carbon in basinal sediments is speculation that lacks documentation. Fermentation has been demonstrated to produce extreme \textsuperscript{13}C values, and, if accepted here, it must proceed to a very modest degree to uniformly enrich the
Smackover and Buckner dolomites compared to south Arkansas - east Texas Smackover and Buckner dolomites (Arkansas values = Stamatedes, 1982; Texas values = Moore and others, 1988). The upper Smackover Texas oomoldic (north = N and south = S) dolomites and the south Arkansas oomoldic dolomite agree well with Jay area oomoldic upper Smackover dolomites. The three unmarked fields are from Figure 33.
- Arkansas Buckner Dolomite
- Texas Buckner Dolomite
- Arkansas oomoldic Dolomite
- Texas oomoldic (N) Dolomite
- Texas oomoldic (S) Dolomite
- Arkansas post-compaction Dolomite
- Texas post-compaction Dolomite
- Saddle Dolomite (Arkansas & Texas)
carbon by only a few parts per mil. The average carbon values (average = +3%) of the Holocene Abu Dhabi dolomites (McKenzie, 1981) need only be enriched by 2% to match the Buckner carbon values. Alternatively, therefore, slightly higher temperatures of dolomitization (Aharon and others, 1977; $\delta^{13}C = 4.1\%$), or slightly enriched predolomite sediments may explain the observed values (Vinet, 1982, 1984). Lowenstam and Epstein (1957) reported Bahamian algae with up to +5.9% $\delta^{13}C$, and Lloyd (1971) suggested that algal photosynthesis may leave residual dissolved bicarbonate enriched in $^{13}C$. Consistently positive $\delta^{13}C$ carbonate components of south Arkansas upper Smackover led Moore and Druckman (1981) to conclude a "constant internal carbon reservoir" was unaffected by plant derived $CO_2$. Considering the limited nature of carbon reservoirs, especially a Jurassic, marine bicarbonate reservoir with little or no terrestrial $CO_2$ influx, Buckner carbon values are reasonable and acceptable without using mechanisms described by Rudolph (1978) and Clark (1980).

The Buckner (and uppermost Smackover, Figure 33 and Plates I-VII) dolomites seem to be 2-3% heavier in carbon than the theoretical estimates. There can be no doubt, however, that they were formed in evaporated seawater. Perhaps, isotopic oxygen and carbon values of the Smackover and Buckner dolomites should be viewed qualitatively, and considered with respect to themselves (with Buckner dolomites as a reference point) and to a lesser degree to other ancient dolomite analogues.

Lower Smackover: The twenty-two samples of lower Smackover dolomite have an average $\delta^{18}O$ of -0.8% (Figure 33). This average is
2.3%, lower than the Buckner average and 1.2% higher than the upper Smackover average. The difference between the upper and lower Smackover may be less than the stated values because of possible contamination by $\delta^{18}O$ enriched saddle dolomite (expected to be -5% $\delta^{18}O$ or lower, see following paragraph). Although an effort was made to avoid sampling lower Smackover where saddle dolomite was abundant, some contamination is probable. Saddle dolomite is usually absent in the upper Smackover dolomites whereas its content in the lower member dolomites may reach up to 5 percent. The average $\delta^{18}O$ of the lower member would be 0.25%, higher if 5 percent saddle dolomite content is assumed. The $\delta^{18}O$ values of the lower Smackover dolomites are similar to the Lower Cretaceous shelf dolomites described by Sass and Katz (1982) which were thought to have been in equilibrium with normal to slightly evaporated seawater (Figure 36). The lower Smackover oxygen values are lower than those of the Buckner due to lower salinities and to lower temperature of formation (evidenced by less abundant nodular mosaic anhydrite).

The $\delta^{13}C$ of the lower Smackover dolomite is compatible with that of dolomite forming in seawater today (Behrens and Land, 1972; Aharon and others, 1977; Sailer and Moore, 1986). Keith and Weber (1964) and Magaritz (1975) suggest that carbon isotopic ratios are resistant to re-equilibration. If this is true, the $\delta^{13}C$ of the lower Smackover dolomite is a product of the Jurassic marine bicarbonate reservoir and the bioclast-pellet carbonate precursor.

Smackover carbon signatures may have changed during moderate burial diagenesis because elsewhere along the Smackover trend, post compaction calc spar cements have similar positive carbon
values. They certainly precipitated at elevated temperatures found under moderate burial conditions (Moore, 1985; but likely less than 100°C according to Hedari and Moore, 1989) yet prior to hydrocarbon migration (Hedari and Moore, 1989). This indicates that a positive Smackover bicarbonate reservoir was available during considerable burial. Since the reactions of bacterial oxidation (vadose), biochemical (shallow burial), and thermochemical fermentation (deep burial) of organic matter all tend to create extreme carbon values (+15% to -80%, Irwin and others, 1977; Hudson, 1977; Lohmann, 1988), it is obvious that none of these processes were dominant during Smackover and Buckner dolomitization. Sulfate reduction also creates extremely low carbon values (Irwin and others, 1977). Therefore, the carbon values of Smackover diagenetic products throughout the trend are of little diagnostic value except for the calcite cements in the deepest parts of the basins (Heydari and Moore, 1989). In addition, organic matter in deep sea sediments promotes sulfate reduction thus increasing dissolved bicarbonate and calcite precipitation. The decreased Ca++ in solution causes an increase in Sr/Ca in solution and thus creates high Sr content dolomite (from 480 - 1290 ppm Sr; Baker and Burns, 1985). There is very little calcite cement in the Jay area and post-compaction saddle dolomites in east Texas have less than 140 ppm Sr (Moore and others, 1988). Therefore, sulfate reduction during the formation of these dolomites was probably minor. 

Taken collectively the $^{18}$O and $^{13}$C isotopic composition of the Buckner, uppermost Smackover and lower Smackover dolomites are compatible with ideas of syndepositional evaporative mechanisms of dolomitization.
Upper Smackover: The oxygen isotopic values for the upper Smackover dolomites form another population and are approximately 3% lower than those of the Buckner Formation (Figure 33; Table B-4, Appendix B). Thirty-two samples have an average $\delta^{18}O$ of -2.0%. These lower oxygen values are difficult to explain if hypersaline waters were the cause of dolomitization. If the upper Smackover rocks were dolomitized by the reflux of Buckner brines (fluid $\delta^{18}O$ of approximately +4% PDB), water temperatures should be considerably cooler than at the sabkha surface thus forming even heavier (than Buckner) $\delta^{18}O$ composition dolomites.

Alternatively, Smackover dolomite $\delta^{18}O$ values can be explained by formation at or near surface conditions in seawater or seawater mixed with meteoric water. Compared to the Buckner, uppermost Smackover and lower Smackover dolomites, all that can be said about the upper Smackover with respect to oxygen alone is that the upper Smackover dolomitizing waters were lower in salinity. If the oxygen values are taken rigidly the upper Smackover value of -2% is compatible with mixed marine-meteoric water composition. If we allow a 2-3% flexibility due to protodolomite stabilization (recrystallization) or our lack of knowledge of true Jurassic seawater $\delta^{18}O$, either normal seawater or mixed marine-meteoric water mechanisms seem plausible.

Dolomitization of Cenozoic age sediments by normal salinity seawater is suspected in a number of recent studies (Saller, 1984; Baker and Burns, 1985; Aharon and others, 1987; Burns and Baker, 1987; Aissaouri, 1988). The best case is in deep sea sediments where pore waters are available for measurement. For the upper Smackover
dolomite $\delta^{18}O$ to be acceptable for normal seawater dolomitization, $\delta^{18}O$ of Jurassic seawater would have to be 2-3% lower than seawater is today.

To test the mixed marine-meteoric water mechanism, let's assume that the Jurassic meteoric water of the Gulf Coast had an isotopic composition similar to Pleistocene meteoric water of the Caribbean, (Land and Epstein, 1970; Ward and Halley, 1985, Lohmann, 1988) the range of Smackover $\delta^{18}O$ (-0.2 to -3.6% PDB) is similar to $\delta^{18}O$ of present day Jamaican meteoric water (-1.3 to -3.7% SMOW, Land and Epstein, 1970) and its products (-0.9 to -3.4% PDB for dolomite of the upper Pleistocene Falmouth Formation (Figure 38) (Land and Epstein, 1970; Land, 1973a). The Late Pleistocene dolomites in the subsurface of the eastern Yucatan coast are considered to be of mixed marine-meteoric waters but have slightly higher (than Falmouth Formation) $\delta^{18}O$ values (Figure 38) (average $\delta^{18}O = 1.7\%$, Ward and Halley, 1985). They preferred mixed waters with a strong marine signature (75% marine - 25% meteoric) to explain the difference when compared to the Falmouth dolomites. An important study was made by Magaritz and others (1980) who reported the formation of dolomite ($\delta^{18}O = -1.3\%$) in a present-day mixing zone near fresh water springs along the Israeli Mediterranean coast (Figure 38). Significant isotopic studies of limestones (Gross, 1964; Allen and Mathews, 1977; Magaritz and others, 1979) demonstrate how whole rock $\delta^{18}O$ become more negative with an increasing volume of freshwater cements. Hence, increased meteoric water influence in the dolomitizing process should result in progressive $O^{18}$ depletion in rocks. Some workers think the $\delta^{18}O$ of the sediment is retained during dolomitization in a
Figure 38.

Smackover and Buckner dolomites compared to dolomites of suspected mixed water origin. The three unmarked fields are from Figure 33.
partly closed system (Land, 1973 b). In the Smackover, influence by the $\delta^{18}O$ of the pre-dolomite sediments is unlikely because rocks with oomoldic fabric in the Buckner have $\delta^{18}O$ enriched by 3 to 4% relative to similar oomoldic upper Smackover dolomites (Stamatedes, 1982; Vinet, 1984; Moore and others, 1988).

One final observation about relative oxygen differences is that there is a 3.73% difference between average Persian Gulf evaporative dolomite $\delta^{18}O$ values (Holocene age; McKenzie, 1981) and average Falmouth Formation (120,000 years old; Land and Epstein, 1970, and Land, 1973a) dolomites of probable mixed water origin. A similar oxygen isotopic difference (3.5%) exists between the average Buckner (evaporative) and upper Smackover dolomites.

The upper Smackover dolomites, though considered to be of a different origin than Buckner dolomites, have similar $\delta^{13}C$ values (Figure 33). This seems to indicate a similar carbon source and, as with the Buckner, uppermost Smackover and lower Smackover, implies an epigenetic dolomitization process free of organic carbon involvement. The source of carbon must be the marine bicarbonate reservoir either from seawater ($\delta^{13}C = +3.5\%$, Lohmann, 1988) or the marine sediments (oolites = $\delta^{13}C = +5\%$). Dolomitization by normal to slightly evaporated seawater could produce such carbon values and was proposed at Big Escambia Creek by Sailer and Moore (1986).

It is also possible to explain upper Smackover $\delta^{13}C = +5\%$ by seawater dominated mixed marine brine-meteoric water as suspected in east Texas by Moore and others (1988). In east Texas, oolites were considered the source of the heavy carbon isotopes. Four things could promote heavy carbon in Jay area dolomites. First, the vadose
zone may have contained little organic matter, which is reasonable in
the arid Smackover environments and indicated by heavy carbon values
in meteoric cements and oomoldic calcites and dolomites throughout
the trend (Moore and Druckman, 1981; Vinet, 1982; 1984; Stamatedes,
1982; Moore and others, 1988). Second, calcium carbonate in
equilibrium with atmospheric CO₂ should have 8^{13}C of between +3 and
precipitated in near surface settings with open system atmospheric
exchange, as suspected with the porous upper Smackover oolite
grainstones, will have indistinguishable coevally precipitated marine
and meteoric carbonates with respect to isotopic carbon (Lohmann,
1988). Third, bicarbonate enriched in C^{13} is produced by algal
heavier than their sediments (as in Jamaica, Land and Goreau, 1970)
are suspected to be the result of algal photosynthesis. Algal
boundstones and algal dominated Smackover sediments in the vicinity
of Jay Field are well documented (Leiker, 1977; Baria and others,
1982; Crevello and Harris, 1984; Green, 1985; Saller and Moore, 1986;
esposito and King, 1987). Fourth, and perhaps the most important
potential source of heavy carbon is the Smackover ooids which were
dissolved (Vinet, 1982, 1984). Recent ooids at Scooner Cay, Bahamas,
average +5%. 8^{13}C (Lowenstam and Epstein, 1957). If the upper
Smackover dolomite, which is nearly all grainstone, was originally
oolite grainstones, a large reservoir of heavy carbon would exist in
the original oolite precursor sediment. Ward and Halley (1985) also
suspected that Yucatan carbonate sands (8^{13}C = +3 to 4%) were the
likely source for the heavy $^{13}$C (average +2.1‰) of the Late Pleistocene Yucatan mixed water dolomites.

Land (1973a) reported dolomites of suspected mixed marine-meteoric water origin with $^{13}$C values near -9‰ PDB. It should be pointed out that they are associated with meteoric systems in a tropical setting where thick organic-rich soils abound. Soils in arid environments are poorly developed or absent and meteoric waters in the Jay area would have come from rainfall (as opposed to ground waters) over exposed oolite shoals. Also, where significant evaporation and CO$_2$ degassing occur, speleothem chemistry has been shown to have markedly enriched $^{13}$C relative to meteoric values (Lohmann, 1988).

The Smackover strandline setting west of the Jay area may provide insight to the carbon problem. The apparent lack of organic influence may be due to a Blackjack Creek-Jay-Big Escambia Creek Late Jurassic insular setting well isolated from the mainland, which could be a potential source of organic CO$_2$ rich waters. However, the south Arkansas Smackover is a strandline setting and there is no indication of light carbon influence even in the northern diagenetic zone dominated by meteoric diagenesis (Moore and Druckman, 1981; Stamatedes, 1982; Moore and others, 1988) (Figure 38). In spite of meteoric diagenesis, in the Arkansas, east Texas and Mississippi northern diagenetic zones, the consistent heavy carbon values in oomoldic calcites and dolomites indicate recycling of a local carbon source, probably from the original sediment in a rock dominated system. Therefore, it is suspected that the sources of upper Smackover carbon were from (1) seawater - probably evaporated
seawater of 60 to 80 parts per thousand NaCl with $^{13}\text{C} = +3.5\%$; (2) recycled carbon from the ooids ($^{13}\text{C} = +0.5\%$); and (3) atmospheric rainfall ($^{13}\text{C} = +4\%$). These sources of heavy carbon could have masked any light carbon from the poorly developed soils especially if dolomitization occurred in seawater dominated portion of the mixed water lense.

There is an approximately 2\% difference between the lower Smackover $^{13}\text{C}$ (average $^{13}\text{C} = +3.0\%$) and the upper Smackover and Buckner $^{13}\text{C}$ (average $^{13}\text{C} = +5.3\%$) (Figure 33). This may be explained by bacterial sulfate reduction or secular variations in the seawater carbon isotopic composition. Epigenetic bacterial sulfate reduction is stated to cause extreme and wildly differing carbon values (-16 to -25\%; Irwin and others, 1977; Hudson, 1977; Lohmann, 1988). The lower Smackover carbon occupies a narrow positive range from +2.0 to +4.1\%. Secular variation may offer a better explanation. Carbon isotopic analysis of early Jurassic pelagic sediments led Jenkins and Clayton (1986) to conclude that a 3\% change had occurred in the oceanic bicarbonate reservoir during the Toarcian. They correlate this change to regional organic rich shale deposition. The Smackover is late Jurassic in age (Imlay and Herman, 1984; a span of approximately 5 million years) and was probably deposited over the span of one or two million years. The change in oceanic carbon isotopic compositions are suspected to occur rapidly. Conceivably, late Jurassic oceanic carbon isotopic composition could have changed 2\% during the time difference between the syndepositional dolomitization of the upper Smackover - Buckner and lower Smackover. Alternatively, the heavy upper Smackover and
Buckner carbon signature may simply reflect the recycling of heavy carbon from the oolite dominated sediments.

Saddle dolomite: Previously described petrographic evidence shows saddle dolomite is a late void-filling cement which postdates all other dolomitization. This is consistent with a single saddle dolomite analysis (-4.9‰) having the lowest oxygen isotopic composition of all the dolomites (Figure 33). The sampling technique used to pick the saddle dolomite crystals invariably resulted in some contamination by surrounding host rock. Thus, the actual $\delta^{18}O$ value of the saddle dolomite phase is probably somewhat lower than the analysis indicates. Using the expression from Irwin and others (1977), the temperature of formation can be calculated to be near 120°C indicating precipitation at approximately 8,000 feet of burial using for the present geothermal gradient (Hanor, 1979) and a $S_w$ of +5.5 from south Arkansas Smackover brines (Moore and Druckman, 1981). Stamatedes (1982) and Moore and others (1988) reported slightly lower values for saddle dolomites in the south Arkansas and east Texas Smackover (Figure 38). Similar, diagenetically late, pore-filling saddle dolomite in older rocks with low $\delta^{18}O$ values are described by Choquette and Steinen (1980) and Mattes and Mountjoy (1980) in Mississippian and Devonian age rocks respectively.

The $\delta^{13}C$ of the saddle dolomite is similar to Smackover and Buckner dolomites, which indicates a persistent carbon pool. If fermentation is a factor its effects should increase with burial. Therefore, the saddle dolomite phase further discredits fermentation here as an influential process. In Mississippi, the effects of fermentation, or more precisely thermal oxidation of hydrocarbon
gasses, are seen in Smackover deep burial, post hydrocarbon migration calcite cements with radically light (-1.6 to -16.3‰ PDB) carbon isotopic values (Heydari and Moore, 1989). This enabled Heydari and Moore (1989) to recognize two otherwise indistinguishable generations of calcite cement. The positive carbon value of the Jay area saddle dolomite, as in Mississippi, simply indicates precipitation prior to the onset of the thermal destruction of hydrocarbons.

In summary, the Smackover and Buckner isotopic composition seems to have changed little with time and appears to be near their original isotopic values. Simply by comparison to Holocene and ancient dolomites, the Smackover and Buckner δ¹⁸O appear unchanged. If a change occurred, it is probably on the order of 2‰ lighter than predicted values. The Smackover and Buckner carbon values indicate dolomitization occurred prior to hydrocarbon generation. The carbon isotopic values of upper Smackover and saddle dolomite are problematic in two respects: (1) post burial saddle dolomite and post-compaction calcite cements elsewhere in the trend show no sign of sulfate reduction or bacterial fermentation both of which commonly occur in less than 3,000 feet of burial and create extreme carbon values (as low as -80‰; Hudson, 1977; Irwin and others, 1977); (2) if the upper Smackover dolomite is of mixed marine-meteoric water origin, the lack of light carbon indicates either a lack of organic matter at the paleo-surface or the marine bicarbonate carbon dominated over any light carbon contribution. The lack of extreme carbon values does not necessarily mean that sulfate reduction and fermentation of organic matter in the subsurface (nor oxidation in vadose environments) did not occur during precipitation. It may mean
the carbon from the marine bicarbonate reservoir dominated and masked any carbon contribution from organic sources except in the deep subsurface (Heydari and Moore, 1989). Otherwise, the oxygen and carbon isotopic signatures conform to syndepositional mechanisms as stated; highly evaporative seawater for the Buckner, slightly evaporated seawater for the lower Smackover and near normal seawater either slightly hyper- or hypo-saline for the upper Smackover.

Although all Smackover dolomites may have recrystallized in the presence of subsurface brines, the narrow spread of upper Smackover oomoldic dolomite $\delta^{18}O$ in the three areas (Jay area, south Arkansas, east Texas) is a strong indication that they have not recrystallized. Figure 37 shows overlapping data populations for the Jay area upper Smackover oomoldic dolomites (average $\delta^{18}O = -2.0\%$), the south Arkansas upper Smackover oomoldic dolomites, and the east Texas upper Smackover oomoldic dolomites (both north and south together average $\delta^{18}O = -2.65\%$). The chances are considered slim that recrystallization occurred at exactly the same temperature and depth (as indicated by a $\delta^{18}O$ difference in the two areas of only 0.65%, close to the limits of laboratory reliability of ±0.2%) in different parts of the trend. The slightly lighter values for the upper Smackover post-compaction dolomites of Arkansas and Texas (Figure 38) seems to indicate formation at higher temperatures (greater depth) than the oomoldic dolomites but lower temperatures (shallower depth) than the saddle dolomites. The gradual process of recrystallization or direct precipitation at depth should produce a wide range of oxygen values as indicated by the saddle dolomites (Figures 36 and 37) and south Arkansas calcspars (Moore, 1985).
Radiometric Strontium:

Variations in the isotopic ratio of $^{87}\text{Sr}/^{86}\text{Sr}$ with time was predicted long ago by Wickman (1948). Radioactive decay of $^{87}\text{Rb}$ to $^{87}\text{Sr}$ in plutonic rocks was believed to have produced a linear $^{87}\text{Sr}/^{86}\text{Sr}$ increase from ancient to present, until Peterman and others (1970), using calcareous fossils, showed the ratio had fluctuated throughout the Phanerozoic. Veizer and Compston (1974) provided a summary of previous work and indicated that seawater $^{87}\text{Sr}/^{86}\text{Sr}$ is uniform throughout time, and that carbonates, whether biogenic or chemical, precipitated from marine waters will exhibit the seawater ratio at the time of formation. Any change from the expected seawater composition value is thought to be the result of diagenesis. By selecting deep water marine rocks and fossils suspected to be unaltered, additional studies since 1974 (Brass, 1976; Kovach, 1980; Burke and others, 1982; DePaolo and Ingram, 1985) show that seawater $^{87}\text{Sr}/^{86}\text{Sr}$ did radically change with time. The advent of more precise mass spectrometers allowed these workers to gradually construct a useable curve which reveals the probable temporal variation of seawater $^{87}\text{Sr}/^{86}\text{Sr}$ (Figure 39). The curve which resulted has empirical applications for age determination or correlation, but for rocks of known age, the curve has some potential for resolving diagenetic relationships.

The two major sources of strontium in seawater are from cratonic plutonic and oceanic volcanic rocks. Old sialic rocks from cratons are the major source of $^{87}\text{Sr}$ (ratio average = 0.720) and weathering of these rocks produces river water with high strontium isotopic ratios. Mafic volcanics and intrusives are a major source
Figure 39.

Marine strontium isotopic ratio temporal variation (from Burk and others, 1982).
0 100 200 300 400 500 600
MILLIONS OF YEARS

TERTIARY  CRETACEOUS  JURASSIC  TRIASSIC  PERMIAN  PENN.  MISS.  DEVONIAN  SILURIAN  ORDOVICIAN  CAMBRIAN  PC.
of low ratio strontium (ratio average = 0.704). Present day 
$^{87}\text{Sr}/^{86}\text{Sr}$ for seawater and fresh water bodies are 0.7092 ±0.0002 and
0.7160 ±0.0033, respectively. Seawater Sr is assumed to have been 
well mixed to create a constant $^{87}\text{Sr}/^{86}\text{Sr}$ throughout the oceans of
the world at any one instant in time. Therefore, carbonate rocks
which deviate above the temporal seawater curve are suspected to be
diagenetically altered in the presence of cratonic water influence
(waters of higher Sr isotopic composition such as those that have
interacted with siliciclastics containing feldspars). Points located
below the curve represent rocks proximal to convergent plate margins
and oceanic settings (Burke and others, 1982). In fact, so dominant
are the two extreme Sr sources that the overall shape of the curve is
thought to be related to the history of plate interactions and rates
of sea floor spreading.

Fourteen upper and uppermost Smackover samples from two Jay
Field wells (Humble Shell and Exxon Swift, Table 2) were analyzed by
Dick Koepnick and Mobil Research Department in Dallas, Texas. Table
2 and Figure 39 show that the resulting $^{87}\text{Sr}/^{86}\text{Sr}$ values fall
directly on the seawater curve for an Oxfordian - Kimmeridgian age.
The age of the Smackover Formation was determined to be late
Oxfordian (Imlay and Herman, 1984).

In addition, six subsurface brine samples were collected
from Jay area wells which were oil and water productive (see Table
B-6, Appendix B). Of the six samples, two (Wa and WE) appear
uncontaminated by fresh water injection (injected for secondary
recovery project) and yield $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.7082 and 0.7075,
respectively (Table B-6, Appendix B). These values are radiogenic in
Table 2. Radiometric $^{87}\text{Sr} / ^{86}\text{Sr}$ of upper and uppermost Smackover dolomites

Exxon No. 1 Swift 10-5, 10-5N-29W, Santa Rosa Co., Florida, Jay Field

<table>
<thead>
<tr>
<th>FRL No.</th>
<th>Depth+</th>
<th>$^{87}\text{Sr} / ^{86}\text{Sr}$</th>
<th>Lithology Comments (Mineralogy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6031</td>
<td>15,426'</td>
<td>0.70679 +/- 0.00004**</td>
<td>Dolomite</td>
</tr>
<tr>
<td>6032</td>
<td>15,427'</td>
<td>0.70688 +/- 0.00003</td>
<td>Dolomite</td>
</tr>
<tr>
<td>6033</td>
<td>15,431'</td>
<td>0.70693 +/- 0.00003</td>
<td>Dolomite</td>
</tr>
<tr>
<td>6034</td>
<td>15,435'</td>
<td>0.70705 +/- 0.00004</td>
<td>Dolomite</td>
</tr>
<tr>
<td>6035</td>
<td>15,438'</td>
<td>0.70696 +/- 0.00002</td>
<td>Dolomite</td>
</tr>
<tr>
<td>6036</td>
<td>15,460'</td>
<td>0.70692 +/- 0.00004</td>
<td>Dolomite</td>
</tr>
<tr>
<td>6037</td>
<td>15,493'</td>
<td>0.70693 +/- 0.00003</td>
<td>Dolomite</td>
</tr>
</tbody>
</table>

Humble No. 1 Shell 20-1, 20-5N-29W, Santa Rosa Co., Florida, Jay Field

<table>
<thead>
<tr>
<th>FRL No.</th>
<th>Depth+</th>
<th>$^{87}\text{Sr} / ^{86}\text{Sr}$</th>
<th>Lithology Comments (Mineralogy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6038</td>
<td>15,604'</td>
<td>0.70686 +/- 0.00004</td>
<td>Dolomite</td>
</tr>
<tr>
<td>6039</td>
<td>15,606'</td>
<td>0.70694 +/- 0.00005</td>
<td>Dolomite 3 counts</td>
</tr>
<tr>
<td>6040</td>
<td>15,618'</td>
<td>0.70712 +/- 0.00004</td>
<td>Dolomite 3 counts</td>
</tr>
<tr>
<td>6041</td>
<td>15,611'</td>
<td>0.70690 +/- 0.00003</td>
<td>Dolomite</td>
</tr>
<tr>
<td>6042</td>
<td>15,622'</td>
<td>0.70690 +/- 0.00003</td>
<td>Dolomite</td>
</tr>
<tr>
<td>6043</td>
<td>15,629'</td>
<td>0.70693 +/- ?</td>
<td>Dolomite 1 count; weak emission</td>
</tr>
<tr>
<td>6044</td>
<td>15,636'</td>
<td>0.70698 +/- 0.00003</td>
<td>Dolomite</td>
</tr>
</tbody>
</table>

+ Depths approximately correspond with marked sample locations on Plate IV.

* All measurements are made relative to NBS standard strontium carbonate (NBS SRM # 987) for which a value of 0.71014 is assumed. Based on this value 36 measurements of the Eimer and Amend strontium carbonate standard (lot 492327) average 0.70797 with a standard deviation from the mean of 0.00003. With this information, you will be able to calibrate the above measurements with the values provided by Al Steuber.

** Errors are based on the average of four counting runs. Although the Mobil data acquisition scheme differs from the traditional single collector, peak-switching mode of data acquisition, both methods count about the same number of ions. This means that the counting statistics for the two methods are about the same.

Where there are fewer than four runs (counts), the measured value and error is of somewhat lower quality. Sample 6043 clearly represents the least reliable analysis, but it does compare favorably with analyses from adjacent samples. Lower quality measurements mainly reflect the small amount of Sr contained in the original samples and the purity of the Sr isolated from these samples. The combination of these effects led to weak filament emission which limited the total number of ions that could be reliably counted.
comparison to the actual measured upper Smackover dolomite $^{87}\text{Sr}/^{86}\text{Sr}$, which average 0.7069 (Table B-6). The elevated Sr/Ca of the Jay area Smackover subsurface brines (0.034 which is three times higher than sabkha brines) suggests that this radiogenic Sr, upon dolomitization, should mask any inherited Jurassic seawater Sr (conceivably from the precursor rock).

Radiogenic strontium was reported in Smackover calcite cements from south Arkansas (Moore, 1985). The poikilitic calcite cements formed after moderate burial, grain to grain pressure solution compaction (Brock and Moore, 1981; Klosterman, 1981; Moore and Druckman, 1981; Stamatedes, 1982). Staining techniques and two-phase fluid inclusion studies show two distinct calcite cements: zoned mosaic (moderate burial by $S_{\text{O}}^{18}$ of zonations) and unzoned poikilitic (slightly deeper burial by two-phase fluid inclusion data) (Moore, 1985). Strontium isotopic analysis of the ooids (near 0.7070) poikilitic calcite cement (from 0.7074 to 0.7080) saddle dolomite (one analysis = 0.7099) and subsurface Smackover brines show cement precipitation from progressively evolving (toward increased $^{87}\text{Sr}/^{86}\text{Sr}$) Smackover brines during increased burial (Steuber and others, 1984; Moore, 1985). The elevated (above Jurassic seawater, which is near 0.7070) $^{87}\text{Sr}/^{86}\text{Sr}$ was believed to be contributed from Norphlet and Bossier siliciclastics which lie beneath and lateral to the Smackover. The present south Arkansas Smackover brine range ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7081$ to 0.7097) indicates that the cements formed from brines with an evolving $^{87}\text{Sr}/^{86}\text{Sr}$ associated with mixing of brines with siliciclastic derived fluids (Steuber and others, 1984; Moore, 1985).
Closer to the Jay Field area, radiometric Sr (Sr = 0.7074 - 0.7078) was reported in Smackover - Buckner dolomites from the Wiggins-Conecuh basement areas (Barrett and Hardie, 1986; Barrett, 1986). According to the seawater curve (Burke and others, 1982; also Figure 39) these dolomites were either diagenetically altered or were primary precipitates from $^{87}$Sr enriched waters. Barrett (1986) concluded that the Smackover dolomties formed in slightly radiogenic saline fluids (inferred Louann) which passed through the underlying radiogeneic Norphlet terrigenous clastics early in the sediments burial history.

The source of Sr in the Jay area Smackover dolomites is Smackover seawater (either directly from seawater or from a precursor rock which was seawater derived) not only for the agreement with the Sr seawater curve (Figure 39) but also for the lack of other sources. There are no igneous rocks associated with the Smackover in the Jay Field area. Plutonic basement rocks were exposed during Smackover deposition in the updip areas but these are at least 12 miles away. If the plutonic rocks had an influence on the Smackover Sr reservoir, one would expect $^{87}$Sr/$^{86}$Sr signature higher than the actual measured values (Table 2). The Cotton Valley and younger sediments in the Jay area are predominately siliciclastic. Therefore, radiogenic $^{87}$Sr/$^{87}$Sr would also be expected if Cretaceous or younger dolomitizing waters (Prather, 1986) somehow moved downward through the Smackover. A consistant narrow range of $^{87}$Sr/$^{86}$Sr values, as observed here in the Smackover, has been determined in Tertiary dolomites to represent a large homogeneous source which can be offered only by seawater (DePaolo and Ingram, 1985; Aharon and
others, 1987). Caution was expressed by Burke and others (1982) for analysis of dolomites with Sr less than 200 ppm. However, in this report Smackover samples with less than 100 ppm Sr are in good agreement with those of higher Sr concentration (Table 2). Also, there is no noticeable difference between the upper and uppermost Smackover $^{87}$Sr/$^{86}$Sr values.

In summary, the narrow range for the 14 Jay Smackover samples leaves little doubt that the upper and uppermost Smackover dolomites possess Jurassic seawater strontium. It is most probable that oolites were largely the original grain type of the east Texas, Hatter’s Pond - Chunchula and Jay area grainstones (Moore, 1984). It is unlikely that much of the Sr source in the dolomites was the precursor sediment otherwise Hatter’s Pond - Chunchula dolomites (Barrett, 1986) and east Texas northern oomoldic dolomites (Moore and others, 1988) would have Jurassic seawater $^{87}$Sr/$^{86}$Sr values as well. Therefore, dolomite formation at Jay probably occurred in a late Jurassic seawater dominated hydrologic system prior to the arrival of radiogenic Sr-bearing brines. This constraint eliminates dolomitization mechanisms which require post Jurassic waters of any kind (Prather, 1986; Lloyd and others, 1986) or pre-Callovian Jurassic waters which migrated upward from compaction and dewatering of the underlying siliciclastic Norphlet sediments in fairly early burial stages (as suspected in the Hatter’s Pond area by Barrett, 1986). If mixed marine-meteoric waters were involved, the fresh water would probably have been in the form of rainwater (insular setting) as opposed to surface run off otherwise Sr$^{87}$ enrichment from.
continental run off, would be expected as in the east Texas northern oomoldic dolomites (strand line setting) (Moore and others, 1988).

**Discussion**

Chemical discontinuity: The most significant discovery of this project is the observed discontinuity (recognized by a change in rock fabric and rock chemistry) which exists within porous and permeable upper Smackover grainstones in Jay and Blackjack Creek Fields (Vinet, 1982, 1984). It occurs within porous grainstones, therefore, it is a diagenetic boundary which represents a contact between either: (1) the rocks and the atmosphere (surface of exposure), (2) the air and water in pore space (water table), or (3) two different waters (density segregation). As seen in Figures 24, 25, 26, 40, 41 and 42 the discontinuity is 6 to 30 feet below the top of the Smackover Formation and exists within porous and permeable dolomite in all three cases. It is marked petrographically by an abrupt change in crystal size from less than 50 μm above to 100 to 350 μm below the discontinuity. Oolite and mixed oolite peloid grainstones are the dominant rock types across the chemical boundary (Figures 40, 41 and 42). In Jay Field, in the Humble Shell well the boundary lies between 15,613 and 618 (Figure 40). Of stratigraphic importance is that a possible caliche occurs at 15613 and a breccia (originally observed in Blackjack Creek Field by Wagner, 1978) occurs a few feet below (Plate IV). This relationship suggests possible exposure to surface conditions. Anhydrite stringers above the discontinuity seem unaffected by dissolution. In Blackjack Creek Field, the discontinuity occurs in the Exxon #15 W. St. Regis well at 15,046 with a similar change in dolomite crystal size above and
Figure 40.

Detailed Smackover-Buckner chemistry of Humble #1 Shell 20-1. The change in dolomite crystal size and chemistry at 15616 occurs within porous and permeable grainstones. If the breccia at 15618 represents a dissolved anhydrite bed then one would expect that the associated dolomites would have evaporative chemistry as the ones above 15616.
Figure 41.

Detailed Smackover-Buckner chemistry of Exxon #1, Swift 10-5. The uppermost Smackover zone in this case is 20 feet thick the dolomites of which are calcian, finer crystalline, higher in $\delta^{18}O$ and trace element composition than the coarsely crystalline upper Smackover dolomites below 15442. Again the abrupt change occurs within porous and permeable oomoldic grainstones.
Figure 42.

Detailed Smackover-Buckner chemistry of Exxon #15 W. St. Regis. Note the same relationships just mentioned in Figures 40 and 41. The uppermost Smackover is 6 feet thick and a breccia is present at the spot where a change occurs in crystal size and chemistry in this well.
below. The breccia at 15,046 is an indication of either a subaerial
surface or the dissolution of an anhydrite layer. In the Exxon Swift
the discontinuity occurs between 15439 and 443. The interval from
15440 to 443 is transitional petrographically with less than 50 um
size crystals above, and approximately 150 um size crystals below
with no lithologic evidence for exposure (Plate V). The stratigraphy
above the boundary is similar to the Humble Shell. These two wells
studied in Jay Field may not be representative of the actual
paleo-relief. The Jay Field porosity isopach map by Ottman and
others (1973) shows much greater porosity in the eastern half of the
field. The area of thick porosity may be due to depositional facies
(area of thicker grainstone units) or more extensive meteoric
diagenesis (area highest above sea level resulting in thicker fresh
water lense and more extensive dissolution). Therefore, the eastern
part of the field may have had greater surface relief and a thicker
vadose zone. This may have resulted in better developed caliches and
rubble zones toward the east. To resolve this, Powell (1984) took a
closer look at the field. Rocks were evaluated from eight additional
wells which revealed no new evidence (caliche, exposure breccias,
etc.) for subaerial exposure. She recognized the discontinuity in a
number of additional Jay Field wells (Figures 43, 44 and Plate XVI).
As in this study, the discontinuity is marked by an abrupt change in
dolomite crystal size and the occurrence of anhydrite layers above,
but not below the discontinuity. Her detailed cross section through
the field (Plate XVI) shows lateral continuity of the uppermost
Smackover zone and apparent flatness or horizontality of the
discontinuity. This suggests that the chemical discontinuity more
Figure 43.

Detailed Smackover-Buckner chemistry of the Humble Moncrief #10-2, located in the northwest quarter of Section 10, 5N-29W, Santa Rosa, Florida (see Plates VII and XIV). Note the abrupt change in crystal size and $\delta^{18}O$ at 15417 (+2 feet) within very porous grainstone section (Powell, 1984).
Figure 44.

Detailed Smackover and Buckner chemistry of the Humble Braxton #21-1, located in the northeast quarter of Section 21, 5N-29W, Santa Rosa, Florida. The chemical discontinuity must lie within the porous interval from 15705 to 15708. (Powell, 1984).
accurately represents the effects of a paleo-water table as opposed to a surface of exposure.

The Humble Braxton, Humble Mongrief (Figures 43 and 44) Exxon Swift and particularly the Humble Shell (Figures 41 and 40, respectively) exhibit a zone of very coarse crystal size (up to 350-380 μm) and high porosity within the few tens of feet below the discontinuity. This coarse crystal zone of higher porosity is due to either higher pre-dolomite porosity and permeability or a prolonged post depositional period of more active dolomite precipitation along a persistent pathway of greater water movement or some combination of the two. If the increased porosity and large crystal size represents a preferred pathway of water movement having caused prolonged diagenesis, two possibilities, with respect to the origin of the discontinuity, exist: (1) shallow burial hydrology in place during incipient Buckner deposition (Powell, 1984; see Appendix C); or (2) a water table, the upper surface of which is marked by the discontinuity. The shallow burial idea (see Appendix C) would: (1) have less dense meteoric connate water in the upper Smackover overlain by dense evaporative brines of the Buckner-uppermost Smackover sediments, (2) require a permeability barrier (not noticed) to isolate the uppermost Smackover from the upper Smackover dolomitization event, or (3) cause a bimodal crystal size and chemistry in the uppermost Smackover dolomites thereby creating a gradual vertical chemical gradient and not a sharp and laterally persistent surface of discontinuity.

If the discontinuity represents the upper surface of a water table, one would expect: (1) a sharp chemical changes within
porous and permeable rock, (2) greater porosity at, or just below the surface of exposure, and (3) apparent flatness or some degree of horizontality (Plate XVI). These three features are observed along with a segregation of crystal size ranges above and below the suspected water table (Figure 45).

In Blackjack Creek Field (Wagner, 1978) the thick (11 feet) brecciated zone in the Exxon Moore 23-E (Figure 46) is of considerable importance. Though no chemical support is available, the reddish brown crusts around grainstone clasts within the brecciated zone, its thickness and the calcite minerology can only be interpreted as that of an oxidized paleo-surface of exposure. In addition, the 1 to 2 foot anhydrite beds in the uppermost Smackover of the Humble Shell and Exxon Swift are separated from grainstones by approximately one foot of muddy carbonate sediments. If solution of anhydrite were the cause of the brecciation, the resulting breccia probably should be composed of muddy clasts. The eleven feet of breccia in the Exxon #1 Moore 23-E and the breccia in the Humble St. Regis 14-4 (Figures 46 and 47) (Wagner, 1978) probably represents a surface of exposure because oolite grainstone fabric is recognized in most breccia clasts. If the high porosity and the breccias represent surface exposure zones, great significance must be given to the magnitude of the subaerial exposure event, the effects of meteoric waters being attributed to one major event as opposed to, or in addition to, numerous subaerial exposures of lesser duration. Blackjack Creek breccias (in three wells) were further discussed by Mitchell-Tapping (1988) who considered them to be products of fresh
Figure 45.
Comparison of rock fabric and crystal size above and below the discontinuity. All four photos are the same scale.
Chemical Discontinuity
Lithologic description of the Exxon Moore 23-E (located in the southeast quarter of Section 23, 4N-29W). Note that the breccia clasts are composed of oolite grainstone and that red-brown stain lines clasts, both of which suggest subaerial exposure as opposed to solution collapse of an anhydrite layer. Also, the decrease in percent dolomite within the breccia zone (dedolomite?) suggests exposure to surface conditions. The comments in unit 3 suggest the chemical discontinuity lies between 15920-928 (from Wagner, 1978).
WELL: EXXON NO. 1 MOORE 23-E
LOCATION: 23-4N-29W
CORE THICKNESS: 122'

LITHOLOGIC DESCRIPTION

UNIT 1, lt. gray, massive mottled anhy. and dol.: contains gray anhy. which appear to be irreg. teedled.

UNIT 2, lt. gray nodular anhy., w/ ol. dk. gray irreg. lapil., and a few anhy. nodules; grates down into core

cols. anhy., w/ irreg. nodular bedding and incr. anhy., nodular.

UNIT 3, dk. gray dol. oolitic past. - gret. w/ dol. porosity (voids 0.1 - 0.75 mm); few fract. Infilled w/
anhy.1 porosity incr. downward, porosity zone slight

towards bedding; ant. of euhedral dol. xla incr. downward.

UNIT 4, brecc. zone w/ lg. gray brown fractured styl.
dol. oolitic past. clasts in dk. gray dol. oolitic gret. w/
dol. porosity only in oolitic gret.; redclay brown stain
lining some clasts

at top of brecc. zone some comp. of gray brown dol.;

15930' - 15935' clasts less distinct; lg. styl.

clasts distinct; abt. styl.; scattered py.

UNIT 5, dk. gray dol. past. - gret. w/ dol. porosity;

burrow, small irreg.7; few fract. and styl.; no py.

15942.5' - 15947.5' tighter; more styl. and fract.

white anhy. xla in irreg. patches (burrows?) or lma.
Figure 47.

Lithologic description of the Humble St. Regis 14-4 (located in the southeast quarter of Section 14, 4N-29W). Note the one foot of breccia at 15808 which is composed of oolite grainstone clasts. Porosity is said to increase downward in unit 4 which may reflect a change in crystal size. According to density-neutron porosity logs, the dolomitized interval from 15802 to 15822 has a consistent 20 to 24% porosity (from Wagner, 1978).
WELL: HUMBLE NO. 1 ST. REGIS 14-4
LOCATION: 14-4N-29W
CORE THICKNESS: 253'

LITHOLOGIC DESCRIPTION

UNIT 1 lt. gray - white anhy.

UNIT 2 lt. med. gray mottled anhy. and dol.

UNIT 3 lt. gray - white mottled anhy. w/ py. cont. along lam: w. lam.

UNIT 4 grad. contact bet. anhy. and brown oolith. dolo. cont. w/ maldic porosity; w. lam? becomes more dolo.

Porosity inc. downward

bioturbation and faint ale

15608' - 15609' intrafr. breccia w/ clasts of brown oolith dolo. grst. in brown oolith grst. w/ scattered anhy.

faint ale

a few fractures and patches of anhy.

becomes v. porous

lam.

a.t. (20°)

becomes more calcitic w/ styl. common and burrows?

UNIT 5 lt. med. gray pellet grst. w/ styl. common and burrows? few maldic porosity; curr. lam.

curr. lam. and a.t. (25°)
water leaching. He shows an area of brecciation located on the southwest flank of the structure.

The Jay and Blackjack Creek, and probably the Big Escambia Creek area as well, were subjected to extensive meteoric diagenesis during a period of subaerial exposure which is represented by the breccias and the chemical discontinuity. The area wide moldic porosity present wherever grainstones exist suggests that a significant island complex existed during the end of upper Smackover grainstone deposition.

There is evidence for extensive upper Smackover meteoric diagenesis across the regional upper Smackover subcrop. Along the updip margins of the basin and on the crests of salt cored bathymetric highs, thick oolite grainstones were dissolved leaving extensive oomoldic limestones and dolomites in south Texas (Loucks and Budd, 1981) east Texas (Harwood and Fontana, 1984; McGillis, 1984; Stewart, 1984; Wilkinson, 1984; Moore, 1984; Moore and others, 1988) south Arkansas (Moore and Druckman, 1981; Stamatedes, 1982; Moore and others, 1989) Mississippi (Badon, 1973; Meendsen and others, 1987) southern Alabama (Leiker, 1977; Bradford, 1984; Barrett, 1986; Esposito and King, 1987) and western Florida (Ottman and others, 1973; Sigsby, 1976; Wagner, 1978; Vinet, 1984; Moore, 1984; Milas and Friedman, 1987; Mitchell-Tapping, 1988). If regional correlations can establish that the upper Smackover oolite grainstone intervals throughout the trend are synchronous, the possibility would exist that the meteoric diagenesis would be as well. This major dissolution event or events can only be explained by fresh waters, as concluded in all of the above sited papers. All other possible
explanations for the moldic fabrics are theoretical possibilities. In Florida and Alabama, the pervasive, early, pre-compaction, low grain density, oomoldic fabrics were apparently caused by a regional sea level lowstand (a few meters seems adequate to expose a considerable area) which produced subaerial exposure in the form of island complexes. The island complexes were marked in the Jay - Blackjack Creek area by the reported chemical discontinuity (Vinet, 1982, 1984; Powell, 1984). Moore (1984) summarizes, "oomoldic porosity is formed by the preferential dissolution of ooids along with concurrent precipitation of intergranular calcite cements, which may later be replaced by medium to coarse-crystalline dolomite."

This general statement applies to all of the upper Smackover dolomite studies to date as well as this one. It is believed that the breccias are the key to documenting the subaerial exposure and they seem to be best developed in the Blackjack Creek Field area. If upper Smackover dolomitization was related to the major meteoric diagenetic episode, it must have occurred in mixed marine-meteoric waters during the latter stages of grainstone dissolution yet prior to uppermost Smackover deposition.

Middle Smackover, Exxon Swift: In the mid-Smackover section of the Exxon Swift well, which is near the structural crest of Jay Field, the chemical composition of the dolomites appears more like the Buckner dolomite chemistry (Figure 25). The interval from 15,520-620 has heavy oxygen values and relatively high Na⁺ compared to the overlying upper Smackover. The grainstone fabric is consistant throughout the interval, although a few muddier, anhydrite nodule bearing beds are present (Plate V). The chemistry
of this interval is an indication that during dolomitization, localized evaporative conditions similar to those of Buckner dolomitization existed and that beds indicative of sabkha conditions may be present in the correlative portions of surrounding wells.

Dolomitization

The dolomites (Buckner, uppermost Smackover and lower Smackover) which are associated with nodular anhydrites conform (chemically and stratigraphically) to widely accepted ideas of dolomitization. They are, therefore, less problematic to interpret and should be discussed first. The following is an evaluation of all models considered feasible for the four dolomites (Buckner and uppermost Smackover, upper Smackover, lower Smackover and saddle).

Buckner and Uppermost Smackover Dolomite

An evaporative origin for the Buckner dolomites receives equally strong support from both stratigraphic and chemical evidence. The stratigraphic evidence includes the shallowing upward uppermost Smackover sequences which cap the grainstone beds in the Humble Shell, Exxon Swift and Exxon St. Regis wells (this report) and the Humble Braxton and Humble Moncrief (Powell, 1984); the association of felted crystal, nodular mosaic anhydrite layers; the intertidal dolomites with fossil assemblages characteristic of highly restricted conditions. Opposite dipping crossbed sets (Plate VI) in the grainstones indicate strong current fluctuations. Subaqueous evaporative conditions are indicated by dark laminated detrital anhydrites in the upper Buckner and terrigenous salt stringer packages (immediately overlying the Buckner, Figure 3) indicative of salinas and salt pans. The oxygen isotopic values are compatible
with the sabkha and salina type stratigraphy. The $\delta^{18}O$ of +0.3 to +3.4$\%$ PDB for Buckner and uppermost Smackover dolomites is similar to modern sabkha dolomites (Kinsman and Patterson, 1973; McKenzie, 1981). The high Buckner $\delta^{18}O$ values do not suggest fresh water influence unless they too are evaporation concentrated (Sibley, 1980). Warren and Kendall (1985) state that in a wet winter, rain water can pond for two or three months on the sabkha surface. Such ponding would create waters with isotopically heavy oxygen. Although the Buckner Sr$^{++}$ and Na$^{+}$ trace element values are slightly low compared to Holocene and Pleistocene analogs, they are higher than either the upper or the lower Smackover dolomite values (Vinet, 1984). Buckner dolomites of south Arkansas and east Texas have similar chemistry and were interpreted as products of evaporative environments (Moore and Druckman, 1981; Stamatedes, 1982; McGillis, 1984; Stewart, 1984; Wilkinson, 1984; Moore, 1984; Moore and others, 1988). Ancient sabkha dolomites interbedded with anhydrites and of relatively close age to Jurassic Buckner dolomites have similar Sr$^{++}$ and $\delta^{18}O$ signatures (Clark, 1980; M'Rabet, 1981). The high excess Ca$^{++}$ is similar to Holocene sabkha proto-dolomites (Kinsman and Patterson, 1973). Buckner dolomites commonly show zoning under cathodoluminescence. Also, diffuse XRD peaks indicate poor crystallinity, which implies that the dolomites are largely unaltered. The dolomites of the uppermost Smackover are interbedded with nodular anhydrites and are considered to be supratidal in origin. The Buckner dolomites have a chemistry similar to uppermost Smackover, but the anhydrites in Buckner appear to be partly supratidal and subaqueous.


**Lower Smackover Dolomite**

Unlike the Buckner dolomite, there is no direct evidence which unequivocally explains the origin of the lower Smackover dolomites. A close approximation is possible by analogy to the Buckner and by a systematic evaluation of alternative models. The lower Smackover is composed predominately of low permeability mud supported matrix so epigenetic dolomite models cannot be used which require the flux of large volumes of water in a short period of time. Reflux from the overlying middle Smackover sediments can be eliminated as a possibility because lime muds and not evaporite rich sediments overlie the lower Smackover dolomites. The Buckner can not serve as a source of brines because it is vertically too far removed, and chemical gradients would be expected through the upper Smackover. Also, it is unlikely the lower muddy sediments would be dolomitized while the middle Smackover muddy sediments are not if a vertical flux of water was involved. Furthermore, if the Buckner brines passed through and dolomitized the upper Smackover on the way to dolomitizing the lower Smackover, the upper Smackover dolomite chemistry should be somewhere between the Buckner and lower Smackover in chemical composition. The case is just the opposite. The carbon isotopic signature of the lower Smackover dolomites is clearly lighter than upper Smackover and Buckner carbon values which indicates two distinct carbon reservoirs.

Late dolomitization by Louann brines is possible but not likely for a number of reasons. The dolomite $\delta^{18}O$ values (average $\delta^{18}O = -0.5\%_o$) are near marine values. They are not low enough to indicate high temperature effects from deep burial conditions as do
the adjacent saddle dolomites (also saddle dolomites of south Arkansas and east Texas) (Stamatedes, 1982; Moore and others, 1988). The Sr/Ca of Louann brines (Table B-6) is high relative to that of sabkha brines (Kinsman, 1966). The low Sr\(^{++}\) content of the lower dolomites compared to Buckner dolomites and saddle dolomites of south Arkansas and east Texas (Stamatedes, 1982; Moore and Others, 1988) argue against highly concentrated brine or Louann brine dolomitization. Dolomites formed in association with past halite brines should be stoichiometric with low sodium and high strontium content (Sass and Bein, 1988). The lower Smackover dolomites are calcian, poorly ordered, low in strontium and high (relative to Buckner dolomite) in sodium, all contrary to predictions of Sass and Bein (1988) for dolomites precipitated from brines that have gone past halite.

Dolomitization by mixed marine-meteoric waters is not very likely. Porosity in the lower Smackover dolomite is in the form of leached pellet fabrics which were probably caused by meteoric water dissolution. Although dolomitization could have caused minor dissolution of calcite, the vast majority of lower Smackover dolomite shows no sign of leaching. Sigsby (1976) describes thick lower Smackover collapse breccias which require considerable and prolonged undersaturation with respect to anhydrite. The thin (approximately 5 foot) beds of leached, moldic fabrics represent a unique event caused, for example, by subaerial exposure. The main lithologic evidence against a mixing model to explain the majority of lower Smackover dolomite is that impermeable, non-moldic dolomite
predominates and that the presence of abundant nodular anhydrite eliminates the possibility of significant fresh water flushing.

A fourth possibility is syndepositional dolomitization by evaporated seawater (2-4 times seawater) brines under conditions of lower salinity than during Buckner dolomitization. Such conditions should produce dolomites with fabrics and chemistry somewhat similar to those of Buckner dolomites. Petrographic similarities include abundant displacive, felted crystal anhydrite nodules, moldic fabrics and fine crystalline (40 µm) dolomite which tends to preserve original sediment fabric. Chemical similarities to the Buckner related dolomites include diffuse XRD peaks and calcian dolomite with up to 9.6 mole % excess Ca$^{++}$. Dolomites with such high excess Ca$^{++}$ are considered to be a product of moderate Mg/Ca (15-25) waters of fairly constant salinity (3-5 times seawater) (Katz, 1971), and not to be a product of low Mg/Ca (1-2) waters (Folk and Land, 1975). The average $\delta^{18}O$ values (-0.5‰) are only 2‰ lower than the average Buckner values (+1.5‰) (an even smaller gap considering some saddle dolomite contamination) and can be explained by slightly lower evaporation rates. The low Sr$^{++}$ and Na$^+$ conform to lower salinities, compared to Buckner conditions. The high excess Ca$^{++}$ in some samples, the ubiquitous poor crystallinity shown by diffuse XRD peaks, the near marine $\delta^{18}O$ and the preserved crystal zonations (of some of the larger crystals) observed by cathodoluminescence indicates the lower Smackover dolomites are probably syndepositional and may reflect their original chemistry.
The relative amounts of nodular anhydrite versus dolomite may indicate the salinity of the waters responsible for dolomitization (Sass, personal communication). The low anhydrite content of an evaporative platform dolomite can be illustrated by a plot of $SO_4^{\text{aq}}$ and $Ca^{++}$ activities (Figure 48). Anhydrite-gypsum saturation is achieved at a concentration of approximately 3.5 times normal seawater. Salinity may fluctuate between 3 and 5 times seawater without much residence time in the stability field of $CaSO_4$, thus producing a rock with small amounts of anhydrite.

Alternatively, if dolomitization occurs at 2-3.5 times normal seawater, the $Ca^{++}$ content of the brines will increase along line A toward anhydrite saturation without a change in salinity. Therefore, salinity need not fluctuate above 3.5 times seawater to produce small amounts of anhydrite. Dolomitization may trigger minor amounts of nodular anhydrite precipitation. The Buckner related dolomites with $\sim$50% nodular anhydrite beds formed under highly evaporative conditions while the lower Smackover dolomite with 5% nodular anhydrite formed under lower salinities.

The lower Smackover dolomite, therefore, probably formed in 2-4 times seawater brines penecontemporaneous with deposition. Large areas were raised to near and slightly above sealevel probably by minor halokinetics of Louann salt thus creating short lived supratidal conditions (collapse breccias described by Sigsby, 1976; anhydrite layers recognized on logs - see Page 20 and by Sigsby, 1976). The regional homogeneity of lithology and thickness demonstrates the uniformity of the restricted conditions. An analogy is units 5 and 6 of the idealized sabkha profile from McKenzie and
Figure 48.

Ca versus $S_0^4$ activity in seawater of increasing salinity. Dolomitization can cause minor nodular anhydrite (or gypsum) precipitation in slightly evaporated seawater outside the Ca$S_0^4$ stability field (less than 3.5 times normal seawater salinity).
$a_{SO_4}$ vs. $a_{Ca^{++}}$

- CaSO₄·H₂O stability field
- 1x sea water
- 2x
- 3x
- 4x
others (1980). Their intertidal lithologies are similar to the lower Smackover lithofacies and are intensely dolomitized to fine crystalline fabric with scattered gypsum mush (McKenzie and others, 1980). Subsidence kept pace with lower Smackover accumulation which prevented supratidal conditions from developing except in localized areas (collapse breccias up to 100 feet thick) described by Sigsby (1976). The chemistry of the interval near 15,665 feet (Figure 25) in the Exxon #1 Swift (with relatively high trace element compositions) probably indicates a period of higher than average salinity. It is suspected, therefore, that more detailed analysis utilizing core from nearby wells (area of structural crest-Jay) may reveal thin beds with anhydrite layers and petrographic fabrics more indicative of localized sabkha conditions during the mostly subtidal deposition of the lower Smackover dolomite.

**Upper Smackover Dolomite**

The origin of the upper Smackover dolomites is more speculative than the others. Certain constraints require that they form in near surface conditions in marine dominated fluids of lower salinity than the Buckner brines. The chemical discontinuity observed in four Jay wells and one Blackjack Creek well is critical to the interpretation of upper Smackover dolomitization. The discontinuity may be present at Big Escambia Creek Field as well but the crucial interval was not cored in the Exxon McCurdy well, nor were the grainstones thick enough for its recognition in the Chevron Scott well. Therefore, based on petrographic and chemical similarities the dolomites at Big Escambia Creek Field are presumed
to be the result of the same processes as those responsible for the
Jay and Blackjack Creek upper Smackover dolomites.

It was shown with the upper Smackover dolomite $^{87}\text{Sr}/^{86}\text{Sr}$
signature that the dolomites formed in a Smackover seawater dominated
hydrologic system. The chemical discontinuity near the top of the
Smackover also puts constraints on possible mechanisms of
dolomitization. There are sharp crystal size and chemical changes
across the discontinuity as described in the previous section and by
Vinet (1982, 1984) and Powell (1984). Any mechanism used to explain
the dolomites must take the chemical discontinuity into
consideration.

The south Arkansas - east Texas upper Smackover oomoldic
dolomites have been petrographically and chemically characterized by
Stamatedes (1982) and recently by Moore and others (1988). Before we
pursue a systematic evaluation of the possible mechanisms for upper
Smackover dolomitization in the Jay area, it would be informative to
compare the similarities and differences between the two areas
(Arkansas - Texas and Florida - Alabama).

The south Arkansas and east Texas upper Smackover oomoldic
dolomites are far removed from western Florida (Jay area) with
considerable paleogeographic differences. Jay area oolites (oomoldic
dolomites) have an off-shore physiographic distribution while south
Arkansas and east Texas oolites were deposited along the margins of a
broad strandline platform setting and interfinger landward (updip)
with siliciclastics (Moore and Druckman, 1981; Stamatedes, 1982;
Harwood and Fontana, 1984; McGillis, 1984; Stewart, 1984; Wilkinson,
1984; Moore, 1984; Moore and others, 1988; Moore, 1989). However,
remarkable similarities exist between the two areas in petrography, Sr and Na trace element chemistry, $^{18}$O and $^{13}$C isotopic character and radiogenic $^{87}$Sr/$^{86}$Sr character. The implication that all these dolomites have a similar origin is inescapable.

Oxygen isotopes, strontium, sodium and pervasive moldic fabrics in both areas suggest upper Smackover dolomitization in an environment affected by meteoric waters (Vinet, 1982, 1984; Stamatakos, 1982; Moore and others, 1988). Radiogenic $^{87}$Sr/$^{86}$Sr ratios in east Texas (Moore, 1988) show a gradient of strong continental meteoric water influence at the platform interior (landward) to a strong Jurassic seawater influence at the platform margins in otherwise indistinguishable (except for crystal size) oomoldic dolomite grainstones. In Florida (Jay area) the $^{87}$Sr/$^{86}$Sr show a strong Jurassic seawater signature and coarse crystal size both of which are similar to the east Texas shelf margin oomoldic dolomites.

The differences between the two areas (east Texas and western Florida) are in strikingly different paleogeography and, consequently, the stratigraphy. In east Texas and south Arkansas the oomoldic grainstones are of a blanket nature on a stable platform, tens of kilometers wide (McGillis, 1984; Stewart, 1984; Wilkinson, 1984). The platform margin grainstones were considered to be a barrier behind which formed evaporative lagoons (Moore and others, 1988). The resulting brines could then mix with meteoric ground waters which moved downdip from the platform interior (northern zone). The updip area at Jay (toward the north, northeast, and east), equivalent to the platform interior in Texas, was the site
of subtidal, low energy, carbonate mud accumulation (see map and cross-section Plates) and can not serve as a lateral source of meteoric ground waters. Another major difference between the two areas is the chemical discontinuity (not observed in Texas and Arkansas) which helps to eliminate certain dolomitization mechanisms.

Dolomitization of upper Smackover grainstones in the Jay area by reflux of Buckner brines seems highly unlikely. In the Jay area there is no evidence, stratigraphic or chemical, to link dolomitization of the upper Smackover to Buckner related brines. The stratigraphic cross-sections D and E (Plates XIV and XV) indicate that the uppermost Smackover is laterally equivalent in part to the lower portion of the Buckner anhydrite in off-structure wells. Certainly dense uppermost Smackover and Buckner brines seeped downward into the porous upper Smackover grainstones during uppermost Smackover deposition and dolomitization. If these brines were to dolomitize the upper Smackover (up to 150 feet below the discontinuity) one would expect high trace element compositions and heavier than Buckner $^{18}O$ due to the lower temperatures (compared to sabkha surface temperatures). How, therefore, can the upper Smackover be 4 per mil lighter in oxygen and lower in Sr and Na trace element composition unless they were already dolomitized by a different mechanism? Also, gradients would be expected and not an abrupt chemical change within porous and permeable oolite grainstone section (note the Humble Shell 20-1, Exxon Swift 10-5 and the Humble Mongrief 10-2, Figures 40, 41 and 43). There is no direct lithologic or petrographic evidence for any sort of permeability barrier.
Deep burial dolomitization in the presence of CaCl brines may be theoretically possible. Smackover subsurface brines are generally described as NaCl saturated Na-Ca-Cl brines expelled from Louann Salt during compaction and modified by dolomitization (Carpenter, 1978), halite dissolution and albitization (Land and Prezbindowski, 1981; Stossel and Moore, 1983). The low Mg/Ca (less than 0.5, Table B-6) compared to predicted past halite Mg/Ca ratios invites the idea of upper Smackover dolomitization by the incipient upward migrating brines. According to Sass and Bein (1988) the ideal stoichiometry and relatively low sodium of the upper Smackover dolomites comply with their model for past halite brine associated dolomites. Contrary to their prediction, however, is the low Sr content. While a moderate burial dolomitization model would help explain 2-phase fluid inclusions, relatively light oxygen isotopic values and stoichiometric, coarsely crystalline, low trace element content dolomite; direct unequivical evidence for the model, such as blotchy cathodoluminescence (Moore and others, 1988; Machel and Anderson, 1989) does not exist. In addition, certain constraints which must be applied to the model greatly limit its potential. These constraints are, first, the very narrow spread of $\delta^{18}O$ values and the superimposing of data clusters (Figure 38) for the oomoldic dolomites of the three areas (east Texas, southern Arkansas, Florida). A subsurface dolomite should precipitate slowly as the brines evolve and create a wide spread in oxygen isotopic composition and trace element composition as observed in the saddle dolomites (Moore and others, 1988) and the zoned, post compaction calcite cements (Moore, 1985). Also, it is highly unlikely that the Texas,
Arkansas and Florida oomoldic dolomites would form at exactly the same temperature and depth in different basins along the trend. Second, recent workers (Sailer and Moore, 1986) observed dolomitization at Big Escambia Creek to have occurred prior to rim cement fracturing (brittle compaction) and pressure solution (stylolites). Third, chemical gradients would be expected and not a sharp chemical "contact" within a porous oomoldic grainstone sequence (Figures 40-45). Another constraint is that the incipient brine must dolomitize prior to the arrival of radiogenic Sr-bearing brines. It seems improbable for burial brines to reach the Smackover without passing them through the underlying Norphlet siliciclastics (in view of recent studies at Hatter's Pond-Chunchula Fields, Barrett, 1986).

Another problem which complicates the burial model requires resistance of the upper Smackover grainstones to dolomitization during uppermost Smackover deposition. This can only be imagined by minerologic stabilization (extensive meteoric water diagenesis, as seen in the south Arkansas, northern diagenetic zone, Moore and Druckman, 1981) of the upper Smackover grainstones (the upper surface of which is marked by the plane of discontinuity) to produce low Mg calcite. The oomoldic, low Mg calcite rock must then resist dolomitization by the dense uppermost Smackover-Buckner dolomitization fluids. They must then become susceptible to dolomitization upon sufficient burial at a temperature indicated by the $\delta^{18}O$ values of the dolomite ($\delta^{18}O$ of -2$\%$o = approximately 35°C if Sw = 1.0%). Also, if this mechanism is feasible, we must explain why the south Arkansas (Miller County area for example) oomoldic limestones were not dolomitized. Other lines of evidence have
equivocal arguments. The 2-phase fluid inclusions may be primary or they may be secondary due to hydrofracturing under burial conditions. Extreme carbon values from oxidation, reduction or fermentation of organic matter may be expected under burial conditions, but not necessarily if inorganic bicarbonate is dominant. The isotopically light oxygen could be from thermal fractionation, or from isotopically light pore fluids. The evidence, therefore, seems much stronger against subsurface brine dolomitization, especially the similarity of $^{18}O$ values is different parts of the trend, widespread oomoldic limestones in the updip areas along the trend, the non-radiogenic $^{87}Sr/^{86}Sr$ signatures (dolomites have Jurassic seawater values), the low Sr content of the dolomites and the sharpness of the chemical discontinuity.

Recrystallization implies two processes: (1) protodolomite stabilization (intracrystalline ordering and exsolution) to ordered dolomite, and (2) burial recrystallization (dissolution-reprecipitation by grain-boundary migration) catalyzed by high temperatures and/or radical change in pore fluid chemistry as connate waters are mixed and displaced by upward migrating CaCl brines (discussed in previous two paragraphs). Recrystallization should confront the same problems just described for direct dolomite precipitation under the influence of subsurface brines. Early burial protodolomite stabilization may explain some of the data but this process is poorly understood. Scientists inability to synthesize stoichiometric dolomite at low temperatures leaves questions unanswered as to whether all dolomites were originally calcian, poorly ordered protodolomites, or if stoichiometric dolomites can be
direct primary precipitates (Hardie, 1987). Recent dolomite (from 160 to 1420 years before present) from Sugarloaf Key, Florida shows that calcian protodolomites become progressively more stoichiometric with age, and that protodolomite stabilization can be a very early diagenetic process (Carballo and others, 1987). If the stoichiometric upper Smackover dolomites were protodolomites that stabilized under shallow to moderate burial conditions (probably less than 3000 feet of burial and prior to the influx of underlying brines) the question arises as to why the calcian, poorly ordered lower Smackover and Buckner dolomites did not stabilize as well. The broad XRD peak shapes of lower Smackover dolomites (Figure 30) indicate not one single dolomite but many dolomites each with different solubility constants depending on the degree of order or nonstoichiometry. Why should the lower Smackover dolomites have partially stabilized (if at all) while the upper Smackover (if originally calcian) stabilized completely? The lower Smackover dolomites are low in measured porosity and permeability from a reservoir standpoint but these rocks were certainly permeable in the context of geologic time. If protodolomites progressively stabilize with increased burial and time (Hardie, 1987), the lower Smackover dolomites should be more stoichiometric. It seems, therefore, that the Smackover dolomite stoichiometry has changed little since the epigenetic origin of the dolomite.

A moderate burial (prior to radiogenic Sr rich subsurface brines) dolomitization mechanism may explain coarsely crystalline, stoichiometric dolomite if fluids were involved of schizohaline (mixed meteoric-evaporated marine, Folk and Land, 1975) composition.
Such waters could have existed if the mixed connate fluids were preserved from the upper Smackover subaerial exposure event. Subsequent burial would cause increased compaction and dewatering, but the hydrologic drive is questionable because at this point the Jay area grainstones were sealed in all directions by impermeable sediments. Although this model (similar to that of Powell - see Appendix C) is compatible with all of the upper Smackover dolomite chemistry, it has questionable hydrology and cannot explain either the sharp chemical discontinuity or the lack of dolomite in similar oomoldic rocks in other parts of the trend.

If dolomitization was a near surface event and no permeability barriers existed at the discontinuity, dolomitization must have preceeded the deposition of the uppermost Smackover sediments. The Smackover has long been regarded as a perfect opportunity to employ the reflux model. The Buckner brine reflux mechanism cannot be tested here if the upper Smackover was dolomitized prior to uppermost Smackover and Buckner deposition. There are three hypotheses which can explain the dolomitization of the upper Smackover prior to uppermost Smackover deposition and in a Smackover seawater dominated system. These are syndepositional dolomitization by slightly evaporated seawater (1.5 to 4 times seawater) less saline than Buckner related brines, dolomitization by near normal salinity seawater and dolomitization by a mixed meteoric evaporated seawater (schizohaline) system. A fourth approach used in southeast Texas (Moore, 1984; Moore and others, 1988) calls for the schizohaline mixing of Ca depleted Buckner brines in the shallow subsurface with an updip supply of meteoric water.
It was concluded that the lower Smackover sediments were dolomitized syndepositionally by slightly evaporated (3 to 5 times normal) seawater. Was the upper Smackover dolomitized by a similar process? The abundance of nodular anhydrite and anhydrite layers in the lower Smackover dolomites was the major evidence for suspecting evaporative conditions. In comparison, anhydrite nodules are rare in the upper Smackover dolomites but at least four muddy intervals in the Exxon #1 Swift were noted to have nodular anhydrite. Also, the chemistry of the middle portion of the Exxon Swift Smackover tends towards evaporative (Buckner like) character. Brines generated during dolomitization of these intervals could have pumped through the porous grainstones from the central part of the Jay complex to its periphery. Anhydrite nodules may have been more abundant, having since been removed (by normal salinity seawater for example) from the porous and permeable grainstone sediments. Most nodules which survived were the ones in low permeability, muddy sediments.

The chemical character, however, of the majority of the upper Smackover dolomites is different from all other Smackover and Buckner dolomites. In comparison, the upper member dolomites are more stoichiometric, better crystalline (ordered) and more coarsely crystalline with lower trace element content and lighter oxygen values (mean $\delta^{18}O = -2.0\%$) than the Buckner-uppermost Smackover (mean $\delta^{18}O = +1.5\%$) and lower Smackover dolomites (mean $\delta^{18}O = -0.5\%$). The upper and uppermost Smackover in the Jay area do have a common strontium source as indicated by the strontium isotopic values in Table 2. The Sr from the precursor sediment is obviously masked by the Sr in the dolomitizing fluids based upon the different
radiometric strontium values in similar oomoldic dolomites across east Texas (Moore and others, 1988) and south Alabama (Barrett, 1986). Therefore, in an open hydrologic system, Sr from the precursor sediment seems insignificant. In the Jay area, this gives rise to the possibility of dolomitization by Jurassic seawater dominated fluids, lower in salinity than the Buckner and the lower Smackover fluids. The lower $\delta^{18}O$ and Na as well as larger crystals are consistent with slightly evaporated solutions (Folk and Land, 1975; Sass and Bein, 1988). Low Sr is somewhat of a problem, but it may be explained by a precursor of second generation calcite rather than aragonite (Sass and Bein, 1988).

Dolomitization models using normal salinity seawater have grown in popularity with better documentation over the past decade (Saller, 1984; Baker and Burns, 1985; Land, 1985; Aharon and others, 1987; Burns and Baker, 1987; Lumsden, 1988; Aissaoui, 1988) even though seawater is widely believed to be incapable of massive dolomitization because of kinetic problems (Folk and Land, 1975; Hardie, 1987). These cases, however, involve atolls or deep sea sediments, where alternative models are difficult or impossible to employ and where considerable time (millions of years) is available for the process to work. Thin crusts (few centimeters) of supratidal dolomite in Holocene sediments appear to be the result of normal to slightly evaporated seawater (Carballo and others, 1987).

Saller and Moore (1986) proposed that upper Smackover dolomitization at Big Escambia Creek was by normal salinity seawater based primarily upon the $S^{13}C$ values. They state that the $S^{13}C$ values are not consistent with dolomitization in a mixing zone. More
precisely though, the positive carbon values are not consistent with mixing zone precipitates where light (organic derived) carbon dominates in the fluids. Mixed marine-meteoric water dolomite in an island free-floating water lense has numerous potential sources for heavy carbon (marine reservoir modified by atmospheric carbon and recycled carbon from oolites as stated on Page 96). It is perhaps more valid though to compare the Jay area upper Smackover $^{13}C$ to Jurassic meteoric diagenesis analogies rather than to the Quaternary as did Saller and Moore (1986). Although considered potentially recrystallized, the south Arkansas northern diagenetic zone limestone and dolomite fabrics (Moore and Druckman, 1981; Stamatedes, 1982; Moore and others, 1988) and east Texas northern oomoldic dolomites (Harwood and Fontana, 1984; McGillis, 1984; Stewart, 1984; Wilkinson, 1984; Moore and others, 1988) are well documented to be the products of meteoric diagenesis with $^{13}C$ ranging from +2.9 to +6.2% PDB. This range is similar to the Jay area upper Smackover $^{13}C$ range of +4.7 to 6.0% PDB (Vinet, 1982, 1984). Considering the problems which confront the lack of organic carbon and thermochemical carbon incorporation in the various Smackover diagenetic products (particularly moderate-deep surface cements as discussed in the carbon isotopic section, pages 92 and 96), interpretations based primarily on the carbon isotopic signature are tenuous.

If the upper Smackover was dolomitized by normal (or slightly evaporated) seawater, it is difficult to relate the timing of dolomitization to the meteoric diagenetic event. There is no reason to believe seawater dolomitization would have occurred after the meteoric diagenetic process because the connate waters would be
partly meteoric. One would expect normal to slightly evaporated seawater dolomitization to have occurred penecontemporaneously with oolite bar development and prior to the meteoric diagenesis. The problem is that it is difficult to explain the moldic arrangement of dolomite crystals if dolomitization was prior to dissolution. It seems far more logical, as concluded by many studies, that the moldic fabric was established and then dolomitized (Moore and Druckman, 1981; Stamatedes, 1982; Moore, 1984; Harwood and Fontana, 1984; Bradford, 1984; Saller and Moore, 1986; Moore and others, 1988).

While normal seawater appears reasonable for small volumes of fabric selective dolomite, it seems inadequate to explain large areas of pervasive platform dolomitization (Hardie, 1987). If upper Smackover dolomitization were caused by seawater, dolomite would be ubiquitous in Mississippi, Arkansas and elsewhere in the Smackover trend, as well as, around the world in modern reefs, shelf sediments, etc.

Upper Smackover dolomitization apparently was caused by seawater modified by either evaporation concentration or meteoric waters or both. The east Texas Smackover studies (McGillis, 1984; Stewart, 1984; Wilkinson, 1984; Moore, 1984; Moore and others, 1988) conclude that there is a direct link in the close association between upper Smackover dolomites and thick Buckner anhydrites. Although of potential significance on a regional scale, the localized pattern in Mississippi, Alabama and Florida is of thin Buckner (and Haynesville) evaporites over Smackover bathymetric highs (whether structural or shoal buildup) (Badon, 1983; Ottman and others, 1973; Barrett, 1984; Koepnick and others, 1985; Meendsen and others, 1987). In Alabama
and Florida, dolomite distribution is a function of grainstone
distribution. In general, grainstones and the subsequent meteoric
diagenesis developed over the bathymetric highs. The chemical
discontinuity and the floating fresh water lense within an island
setting at Jay and Blackjack Creek Fields greatly diminish the
ability to involve Buckner brines in the manner utilized for upper
Smackover dolomitization in east Texas by Moore and others (1988).
The Jay area could not have had the hydrologic drive possible in the
Texas strand line setting, as well as, the dual source of coeval
brines and meteoric waters during Buckner deposition required for the
model. Meteoric waters were essentially shut off from the upper
Smackover once uppermost Smackover-Buckner deposition ensued. The
only way to involve both meteoric waters and brines to create fluids
similar in composition to those suspected in Texas is with an island
setting which existed in the Jay area prior to uppermost Smackover
deposition. Although oolite grainstones in some areas possibly were
originally calcite (Sandberg, 1975; Moore and others, 1986;
Swirydzuk, 1988) it is doubtful that mineral selectivity (favoring
aragonite) could explain dolomite distribution. Most upper Smackover
dolomitization, in any case, was of an oomoldic rock fabric presumed
to be partly stablized to calcite (Moore, 1984).

Dolomitization by mixed (probably evaporated)
seawater-meteoric water offers another mechanism which may explain
the upper member dolomites. The wide spread pervasive moldic
porosity, and closely associated microspar, the possible caliche in
the Humble Shell well, and the breccias and their paleostructural
position over Jay and Blackjack Creek Fields suggest subaerial
exposure and fresh water diagenesis (see pages 109-114). The low Sr$^{2+}$ and Na$^+$ of the upper member dolomites, compared to Buckner and uppermost Smackover, implies dolomitization by solutions of lower salinity. The mean oxygen isotopic values of the upper Smackover dolomites are compatible for dolomites produced under some meteoric water influence. The carbon isotopic values indicate inheritance from a persistant heavy marine bicarbonate carbon reservoir probably influenced by the dissolution of oolites. An insular floating mixed water lense seems an ideal setting for the recycling of the $^{13}$C enriched bicarbonate from oolites (Lohmann, 1987). The well crystalline, stoichiometric upper Smackover dolomite characteristics are compatible with ideas that high Mg/Ca fluids of dilute salinity (mixed evaporated marine-meteoric "schizohaline model") can produce stoichiometric dolomite (Folk and Land, 1975; Hardie, 1987). Figure 49 illustrates how a Smackover seawater of 2-3 times normal (Mg/Ca of 7 or 8/1) would drop into the dolomite field upon the introduction of meteoric water. A fluid with the combination of high Mg/Ca and low ionic strength should be favorable for dolomite precipitation. Although the Smackover hydrology of east Texas and Florida differs, this may be the common ground or genetic link between the similar (chemically and petrographically) upper Smackover dolomites of the two areas.

While the fact that extensive meteoric diagenesis is accepted, there is no guarantee that the fresh water acted as a catalyst to dolomitization. It can be said that the timing of dolomitization and oomoldic porosity development were so close that dolomitization was either because of or in spite of fresh water, and
Figure 49.

Mg/Ca versus salinity emphasizing minerals and their morphologies. (from Folk and Land, 1975)
the mixed meteoric-marine (or marine brine) model should be favored (Feazel, 1980; Loucks and Budd, 1981; Vinet, 1982, 1984; Stamatedes, 1982; Moore and others, 1988). If dolomitization occurred during or after meteoric diagenesis, as indicated by the open, moldic fabrics common to stabilized low Mg calcite rocks, (Moore, 1984) yet before the deposition of uppermost Smackover and Buckner, it may be possible to pump and mix an adequate volume of seawater, or more likely (due to the presence of anhydrite nodules) slightly evaporated seawater, through the grainstone shoal complex at this time. Vigorous tidal action (Budd, 1984; Carballo and others, 1987; Moore, 1989) could pump slightly evaporative brines through the grainstone islands (Figure 50 a) to mix with the floating meteoric water lense (Simms, 1984). Alternatively, evaporative drawdown (north of the shoals) may force (one way northward, Figure 50 b) seawater through the grainstones (Sailer and Moore, 1986).

Problems with the mixing or schizohaline model at Jay is that the area was an island complex with a floating fresh water lense and no possibility of connection to a mainland hydrologic system. However, the requirement for dolomitization is the adequate supply of Mg ions (seawater in this case). This may not necessarily require the flux of large volumes of water if ion diffusion or mechanical mixing is sufficient. Because of the density difference, marine waters can support a column of fresh water 40 feet thick for each foot of elevation of the meteoric water table (Moore, 1989). Therefore, even minor surface elevations at Jay and the homogeneity of the thick, porous grainstones seem adequate for the physical mixing which should result from diffusion and tidal pumping (Budd,
Figure 50.

Schematic two possible mechanisms of dolomitization hydrology. In process A, tidal pumping can move large volumes of water through porous grainstones (Budd, 1984). Evaporative drawdown (process B) assumes seawater flow was constricted around the grainstone shoal areas. The higher Smackover salinities ten miles plus north and northeastward in the updip areas for example (Appleton area, Saller and Moore, 1986) may simply be due to shallower water conditions and not necessarily seawater restriction caused by the shoal areas around Jay.
1984; Carballo and others, 1987; Moore, 1989) through the superporous upper Smackover grainstone sediments. Mixing zones can have considerable thickness beneath oceanic islands with highly permeable sequences (Vacher, 1977; Buddemeier and Holladay, 1977; Moore, 1989). Although mixing models are considered to require time and large fluid flux (Hardie, 1977) it is not the fresh water that needs to be fluxed; seawater is the source of ions which may be constantly replenished by diffusion or mechanical mixing. Hardie (1977) considered time to be a frequently overlooked major diagenetic factor. The time factor should favor all dolomitization processes in epicontinental sea conditions like those which existed during the Late Jurassic. The Quarternary analogues for mixed water dolomites experience radical sea level fluctuations on the order of 100,000 years (or less) per cycle (Land, 1973a; Harmon and others, 1983; Ward and Halley, 1985). This means the residency time of the mixed water zone in any one spot during the Holocene and Pleistocene was perhaps 10,000 to 30,000 years. Much more stable sea level conditions prevailed (relative to the Quarternary) during the Late Jurassic Smackover deposition. Therefore, the time factor (probably hundreds of thousands of years) must increase the potential of mixed water (schizohaline) dolomitization even in a floating mixed water lense situation.

Some of the upper Smackover dolomites seem to have formed in seawater brines. Of the two Jay wells studied, the Exxon Swift well is in the most central paleostructural position. The upper Smackover dolomite has a chemistry in the interval from 15,350 to 15,615 which is more like Buckner dolomites (Figure 25). By analogy
to the Buckner, the high $\text{Na}^+$ values and the heavy $\delta^{18}\text{O}$ values indicate localized dolomitization by evaporated seawater brines probably occurred during upper Smackover deposition and that additional stratigraphic evidence for localized supratidal conditions should lie in the stratigraphic equivalent elsewhere in the field.

In summary, the upper Smackover dolomite has multiple possibilities for its origin. Two upper Smackover dolomites were recognized based upon chemical characteristics. A dolomite of minor occurrence was recognized in the middle Smackover of the Exxon Swift well and is of evaporative origin. The exact origin of the second dolomite occurrence, which represents the vast majority of upper Smackover dolomite, remains equivocal despite the extensive stratigraphic, petrographic and geochemical data base. The two mechanisms which seem most plausible for these dolomites are in order of preference: (1) mixed evaporated marine-meteoric (schizohaline) dolomitization related to subaerial exposure event(s) and dolomitized prior to uppermost Smackover deposition; and (2) shallow burial dolomitization (with Smackover connate fluids at less than 3000 feet of burial) which must occur prior to the influx of radiogenic Sr-bearing (Louann related) subsurface brines. The connate fluids should be a mixture of slightly evaporated water from the underlying lower Smackover stratigraphy and the upper Smackover grainstone fluids which should be schizohaline in composition due to the preservation of the floating lense purged to a certain extent by uppermost Smackover brines. The weakest part of the shallow burial model is the sharpness of the chemical discontinuity, non-dolomitized oomoldic limestones in other parts of the trend, and the probability
of hydrologic stagnation in the Jay area. In order for this
dolomitization mechanism to work, there must be no dolomite
precipitation (new crystals or overgrowths) in the uppermost
Smackover (which would cause chemical gradients) during upper
Smackover dolomitization. There were no permeability barriers to
promote this idea. The weak point related to the insular mixed water
model is the lack of Holocene dolomite which can be attributed to
such a mechanism. In spite of extensive meteoric diagenesis,
dolomite has yet to be discovered in modern insular settings with
free floating meteoric lenses. Modern islands studied, however, have
normal marine phreatic salinities (Mg/Ca = 3:1) and do not qualify as
schizohaline models. The mixed evaporated marine-meteoric mechanism
is favored because it satisfies most of the geologic and geochemical
constraints. A schizohaline mechanism is suspected because the
Smackover seawater probably was slightly evaporated (1.5 to 2.5 times
seawater, due to ubiquitous, though sparse, anhydrite nodules, the
absence of siliciclastic influx, and the lack of normal salinity
seawater fauna such as corals found in south Arkansas). This two or
three fold increase of Mg ions should significantly increase the
dolomitization potential compared to normal marine-meteoric mixing
mechanisms. Also, compared to the more stable Jurassic eustatic
conditions, Quarternary mixed marine-meteoric analogies may be
suspect because we are presently in an interglacial stage: one where
sea level residency time at any one level is short (probably 50,000
years). Table 3 is a flow sheet which provides a quick analysis as
to the merits and weaknesses of the upper Smackover dolomitization
models which were considered in the text. A yes or no means the
Table 3. Upper Smackover Observations

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Dolo. postdates Moldic Porosity</td>
<td>---</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Open moldic - * fabric of dolomite</td>
<td>---</td>
<td>No</td>
<td>Yes</td>
<td>---</td>
<td>No</td>
</tr>
<tr>
<td>Breccias *</td>
<td>---</td>
<td>---</td>
<td>Yes</td>
<td>---</td>
<td>No</td>
</tr>
<tr>
<td>Sharp angular *</td>
<td>---</td>
<td>---</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>nature of breccia</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chalky texture* (microspar)</td>
<td>---</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Early compaction*</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Sharp, flat discontinuity</td>
<td>No</td>
<td>---</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>δ18O = -2.0‰</td>
<td>No</td>
<td>---</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>δ13C = +5.3‰</td>
<td>Yes</td>
<td>Yes</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Sr concentration</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>---</td>
<td>No</td>
</tr>
<tr>
<td>Na concentration</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>---</td>
<td>Yes</td>
</tr>
<tr>
<td>δ87Sr/δ86Sr</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>δ18O compared to Texas-Ark.</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>---</td>
<td>No</td>
</tr>
<tr>
<td>2-phase fluid inclusions</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Insular setting</td>
<td>Yes</td>
<td>Yes</td>
<td>---</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>

Yes = lends support; No = lends weakness; --- = no particular support; ?=???

* observations as a group represent "meteoric diagenesis" and may or may not relate to dolomitization.
observation may lend support or weakness to a particular dolomitization model while a dash indicates no particular support either way. The question mark simply indicates an unknown relationship. The mixed marine-meteoric model is the only one which does not seem to have major condemning criteria.

**Saddle Dolomite**

Saddle dolomite in the Jay area as in south Arkansas (Brock, 1981; Stamatedes, 1982) and southeast Texas (Moore and others, 1988) is a product of late diagenesis. It does not occur as a replacement mineral but as a pore-filling cement which postdates the early formed Buckner, upper and lower Smackover dolomites. In only one sample was saddle dolomite plentiful enough to be plucked by needlepoint in sufficient quantity for a stable isotopic analysis. Using the expression of Irwin and Curtis (1977), which relates the isotopic composition of dolomite and water, a temperature of 110°C (close to measured bottom hole temperatures) for Jay area saddle dolomite formation was calculated from the following expression:

\[
T(°C) = 31.9 - 5.5(Sd - Sw) + 0.17(Sd - Sw)^2
\]

where \( Sd = -5.0 \) (Jay area saddle dolomite \( \delta^{18}O \)) and \( Sw = +5.5 \) (south Arkansas Smackover brine reported by Moore and Druckman, 1981).

Three saddle dolomite samples from south Arkansas yield an average temperature of 116°C (Stamatedes, 1982). East Texas Smackover saddle dolomites have the same range (Moore and others, 1988, in his Table 2, p. 177, dolomites from wells 16 and 17 are Buckner dolomites, not Smackover saddle). The sample analyzed for this report was certainly contaminated by a small amount of earlier formed matrix dolomite enriched in \( O^{18} \). A more realistic temperature of formation,
therefore, is slightly higher than the calculated 110°C value. A still higher temperature would result if the Jay area brines (unknown) are isotopically heavier than the south Arkansas brines. Based on the present geothermal gradient of the northern Gulf coast, saddle dolomite formed between 8,000 and 9,000 feet of burial. The ancient geothermal gradient may have been higher by analogy to rifting continental margins. Therefore, dolomite may have formed at a somewhat shallower depth.

The volumetrically low saddle dolomite content of the Jay area dolomites preclude the ability to produce sufficient samples for trace element analysis. However, a close look at the east Texas saddle dolomites (Moore and others, 1988) allows for a test of the deep burial interpretation used here. The east Texas saddle dolomite Sr (average 121 ppm) content is 2 1/2 times higher than the reported east Texas upper Smackover dolomites (average Sr = 55-64 ppm). It was shown that Sr/Ca of present subsurface brines (0.025 plus = south Arkansas, Moore and Druckman, 1981; and 0.034 Jay area, Appendix B, Table B-6) are approximately 3 times that of sabkha brines. Thus, the higher Sr in saddle dolomites conforms to what must have been high Sr/Ca incipient subsurface brines. Also, the high $^{87}$Sr/$^{86}$Sr (0.709 and 0.710, Moore, 1985; Moore and others, 1988) is compatible with the idea of upward migrating radiogenic dolomitizing fluids (Moore, 1985; Barrett, 1986). It is suspected that the Sr trace element and isotopic ratios of Jay area Smackover saddle dolomites would show a trend similar to that of east Texas saddle dolomites.
Late Diagenesis

The late diagenetic cements are mostly void fill but rock replacement as well. Their chronologic relationship to each other were clearly established with petrographic observations. The para-genetic sequence of the cements and their relative depths of formation are based on cement superposition and illustrated in Figure 51.

1. Sutured seam stylolite (Wanless, 1979) actively postdates the latest cement precipitation, but initiation of the activity probably occurred before precipitation of any of the late diagenetic cements. Cementation may be closely related to stylolite, activity as illustrated in south Arkansas zoned calcite cementation (Stamatedes, 1982). Stylolitization in the Jay area probably commenced shortly after burial, and became increasingly more active during saddle dolomite precipitation, inactive during the latter part of anhydrite precipitation and active again during calcitization.

2. The beginning of sulfate reduction may precede saddle dolomite precipitation. Recent authors (Radke and Mathis, 1980) use sulfate reduction (either organic or inorganic) to promote saddle dolomite precipitation. The inorganic sulfate reduction reaction is favored in acid environments (W. Segried, personal communication). In general, subsurface brines are acid but an indirect indication is the late dissolution effects observed in the south Arkansas Smackover (Moore and Druckman, 1981). Late dissolution may occur at Jay but its effects are not noticeable. Considering that bacterial sulfate reduction is highly improbably above 85°C, that the presently known lower temperature limit of inorganic sulfate reduction is
Figure 51.

Paragenetic sequence for the Jay-Big Escambia Creek area.
<table>
<thead>
<tr>
<th>DEEP BURIAL</th>
<th>MODERATE BURIAL</th>
<th>PRE-BURIAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrocarbon Migration</td>
<td>Poss. Connate Water Dolo. USD</td>
<td>Nodular Anhydrite</td>
</tr>
<tr>
<td>Saddle Dolomite</td>
<td>Stylolitization</td>
<td>Evap. Dolomitization</td>
</tr>
<tr>
<td>Poikilitic Anhydrite</td>
<td>Discoid Gypsum</td>
<td>Blocky Calcite</td>
</tr>
<tr>
<td>Poikilitic Celestite</td>
<td></td>
<td>Dissolution</td>
</tr>
<tr>
<td>Poikilitic Fluorite</td>
<td></td>
<td>Isopachous Cements</td>
</tr>
<tr>
<td>Poikilitic Calcite</td>
<td></td>
<td>Mixed-Water Dolomitization</td>
</tr>
<tr>
<td>Faulting</td>
<td>Dolomitization USD</td>
<td>Mold Collapse Compaction</td>
</tr>
<tr>
<td>Louann Salt Movement</td>
<td></td>
<td></td>
</tr>
<tr>
<td>*Possible Aragonite/Calcite Inversion</td>
<td></td>
<td>Microspar-Chalky Texture</td>
</tr>
<tr>
<td>2-Phase Fluid Inclusions</td>
<td></td>
<td>Soft Sediment Compaction</td>
</tr>
</tbody>
</table>
approximately 200°C (Radke and Mathis, 1980), and that the inorganic reduction reaction is accelerated in acid environments, inorganic sulfate reduction seems more plausible. The rate of thermochemical sulfate reduction is a function of kinetics and is thus a process which begins slowly and continues with increasing burial. Given enough time at 100°-150°C and the probable acid condition of the Smackover brine, inorganic is perhaps more valid than biogenic sulfate reduction in the Jay area. In organic sulfate reduction probably occurred slowly and continued during poikilotopic anhydrite precipitation (Figure 51). This is indicated by the wide variation in $S^{34}$S of Smackover anhydrites. The subsequently produced $H_2S$ may be partly oxidized to produce pyrite and native sulfur. Dolomites produced by bacterial sulfate reduction should have carbon isotopic values depleted in $C^{13}$.

3. Saddle dolomite formed at a temperature of approximately 120°C as suggested by paleotemperature calculations using $S^{18}$O values of the dolomite and of present Smackover brines ($S^{18}$O = +6.7%) from Jay Field. The depth of formation is dependent upon the paleo-ancient geothermal gradient. A higher geothermal gradient means a shallower depth of precipitation is possible. The slow process of sulfate reduction may not best explain the change in conditions which caused the dolomites to precipitate. Precipitation could have began as a result of the injection of Mg and $SO_4$ rich Louann connate brines into the Smackover. Overpressured Louann brines were likely released during Late Cretaceous faulting. The Smackover formation was buried approximately 8,000 feet by Late Cretaceous time which agrees with the estimated temperature of
precipitation (120°C) using the present geothermal gradient. The mixture of Smackover connate water and a past halite brine would produce sufficiently high Mg/Ca to trigger dolomitization (saddle dolomite?).

4. Poikilotopic anhydrite petrographically postdates saddle dolomite but the two cements may have partly coprecipitated.

5. Celestite replaces poikilotopic anhydrite and appears to coprecipitate with fluorite in fractures. Celestite and fluorite precipitation may be related to aragonite-calcite inversion of the upper member lime pellet wackestones. Aragonite can serve as a source for strontium (Schmidt, 1965) and fluorine (Moore, 1972). For the reaction \( \text{CaSO}_4 + \text{Sr}^{++} = \text{SrSO}_4 + \text{Ca}^{++} \) the equilibrium constants \((K)\) indicate that celestite \((K = -6.70)\) is more stable than anhydrite \((K = -4.97)\) at 100°C and 300 bars. If \( K = \text{Ca}/\text{Sr} \) molar ratio, then celestite replacement began either because of increased \( \text{Sr}^{++} \) concentration (aragonite inversion) or from decreased \( \text{Ca}^{++} \) concentration (anhydrite precipitation concurrent with inactive stylolites).

6. \( \text{Ca}^{++} \) and \( \text{CO}_3 \) continued to increase due to stylolitization and possibly hydrocarbon maturation which may have caused calcite to precipitate. Calcitization of anhydrite and celestite occurred at this time. Calcitization of dolomite was either very early during subaerial exposure, or concurrent with calcitization of the sulfate minerals. Although the \( \text{Sr}/\text{Ca} \) ratio in the present Smackover brine is equal to the ratio in sabkha brines, presence of some strontionite may be expected as indicated by the equilibrium constants \((K)\) at 100°C and 300 bars \( K_{\text{CaCO}_3} = -9.25; \)
$K_{SrCO_3} = -11.40$), for the absence of strontionite may be related to unknown kinetic affects.

7. There is no indication that hydrocarbon accumulation overlapped with the above processes. It could not be determined if calcite cementation continued after hydrocarbon emplacement.
CONCLUSIONS

The origin of three of the four dolomite types, recognized in the Jay area can be determined with a reasonable degree of certainty. The two dolomites associated with nodular mosaic anhydrite (Buckner-uppermost Smackover and lower Smackover) conform stratigraphically and chemically to evaporative dolomitization models. The third dolomite type - saddle dolomite, formed as a pore-filling cement under moderate to deep burial conditions based on solid petrographic and chemical evidence. The upper Smackover dolomites are distinctive in appearance and chemistry. Part of the upper Smackover dolomites (the lower portion of the upper Smackover in the Exxon Swift well) apparently formed from syndepositional evaporated seawater. The majority of the upper Smackover dolomites probably formed in floating mixed water lenses which developed during a prolonged regional subaerial exposure event. The waters were probably slightly evaporated marine mixed with meteoric rainwater (schizohaline).

In addition, the following conclusions can be made with respect to the lower Smackover member:

(1) The stratigraphic unit is predominately a low energy, non-moldic, pellet-peloid packstone which is uniform in thickness and pervasively dolomitized throughout the study area. Environment of deposition is restricted shallow marine.

(2) Anhydrite nodules are early diagenetic, soft sediment product of evaporative seawater.

(3) The matrix dolomite is calcian, poorly ordered, finely crystalline which are considered common attributes of
protodolomites (Hardie, 1987), therefore, they are considered to have their original chemistry preserved.

(4) Matrix dolomitization was syndepositional in evaporative seawater ranging from 2 to 4 times normal seawater.

(5) Moldic fabrics were caused by the leaching effects of minor amounts of meteoric water from periodic subaerial exposure during lower Smackover deposition. There is a common association of coarse dolomite crystal size, pelmoldic fabric and white chalky rock texture (microspar).

(6) Saddle dolomite was the first of the diagenetically late, pore filling cements to precipitate. The light oxygen value \( \delta^{18}O = -5\% \) is due to thermal fractionation under burial conditions. The lack of reliable \( \delta^{18}O \) values for Jay area subsurface brines (due to fresh water injection projects, Table B-6) disallows accurate paleo-temperature calculations. The other late cements in order of precipitation are poikilitic anhydrite, celestite and fluorite, and finally, poikilitic calcite cement (Figure 51).

The following conclusions can be made with respect to the uppermost Smackover and Buckner:

(1) The dolomites have high intertidal-low supratidal stratigraphy.

(2) The dolomite formed syndepositionally in evaporative seawater brines.

(3) The dolomites possess relatively high Sr and Na trace element compositions, heavy oxygen isotopic signatures, zoned dolomite crystals and are believed to have their original
chemistry preserved. Their chemistry supports an evaporative origin.

(4) Nodular mosaic anhydrites which cap grainstone complexes over the paleostructural high areas are probably supratidal in origin. The laminated anhydrites are subaqueous in origin. In off paleo-structural positions, the Buckner anhydrite and overlying salt beds thicken and are predominately subaqueous in origin. These evaporites are thin over the upper Smackover grainstone areas (paleostructural high areas) and thick over the upper Smackover lime mudstone areas (depositional low areas).

(5) The isopachous rim cements are either the products of marine waters or meteoric waters during dissolution.

The following conclusions can be made about the upper Smackover member:

(1) Subtidal lime pellet-peloid mudstones to wackestones accumulated in off paleo-structural positions.

(2) Intertidal grainstones accumulated over the paleo-structural high areas which were caused by halokinetics.

(3) Most of the grainstone allochems were ooids or superficial ooids.

(4) Moldic porosity development and bladed calcite cement precipitation were cogenetic. Dissolution of probably aragonitic ooids was followed by precipitation of a portion of this carbonate as isopachous bladed calcite cement (Halley and Harris, 1979; Stamatedes, 1980). Moldic porosity, microspar and chalky rock texture occur together.
(5) A flat surface of discontinuity exists within the upper Smackover dolomites and is marked by breccias, a change in dolomite crystal size and chemistry. The discontinuity is interpreted as a paleo-water table.

(6) The paleo-water table indicates the development of island complexes (with floating mixed water lenses) during a prolonged period of extensive subaerial exposure and meteoric diagenesis. This coupled with the meteoric diagenesis along the trend in the updip areas, as well as over offshore Louann salt induced highs and basement highs indicate a prolonged sealevel low stand or still stand after most of the oolite grainstones accumulated.

(7) The constraints presented by the sharpness of the chemical discontinuity, which occurs within very porous grainstones, heavily favors upper Smackover dolomitization prior to uppermost Smackover and Buckner deposition.

(8) The oomoldic arrangement of dolomite crystals which preserves early isopachous cement morphology and ooid internal structures indicates dolomitization either post dates or was concurrent with the later stages of ooid dissolution or both.

(9) The Buckner dolomites which were encased in impermeable anhydrites can serve as an "internal chemical standard". Therefore, the low Sr and Na trace element content and relatively light oxygen isotopic composition of the upper Smackover dolomites is consistent with formation in mixed evaporated marine-meteoric water. The 3.5% oxygen isotopic difference between the average Buckner (evaporative) and upper
Smackover dolomites is similar to the 3.73% difference between Persian Gulf (evaporative dolomites, McKenzie, 1981) and Falmouth Formation dolomites (mixed water dolomites, Land and Epstein, 1970 and Land, 1973a). The dolomite $^{87}\text{Sr}/^{86}\text{Sr}$ signature of Late Jurassic seawater and consistently positive ($^{13}\text{C} = +5.3\%$) carbon isotopic signature indicates a strong overprint from the precursor oolite grainstones which would be expected in a floating mixed water lense setting.

The late diagenetic cements post date early compaction features, such as mold collapse and brecciation, and matrix dolomitization. Saddle dolomite formed after considerable burial (probably greater than 8000 feet) and was the first of the late cements to precipitate. The rest formed in the general chronologic order of poikilitic anhydrite, celestite, fluorite and calcite. Saddle dolomite and poikilitic anhydrite may be partly cogenetic. Celestite and fluorite seem to be cogenetic and may be realted to the inversion of aragonite to calcite. Stylolites truncate all cements but activity probably was sporadic through the burial history.
BIBLIOGRAPHY


251


Borono, T.C., 1984, Petrography and diagenesis of the Upper Smackover Formation (Oxfordian), Atlanta and Pine Tree Fields, southwestern Arkansas: unpublished M.S., University of New Orleans.


Folk, R. L., and Assereto, R., 1974, Giant aragonite rays and baroque white dolomite in teepee fillings, Triassic of Lombardy, Italy (abs.): AAPG-SEPM annual meeting, v. 1, p. 34-35.


Fritz, P. and Jackson, S. A., 1972, Geochemical and isotopic characteristics of Pine Point, Northern Canada: 24th International Geological Congress, Montreal, Canada, Sec. 6, p. 230-243.


Halley, R. B., and Harris, P. M., 1979, Fresh water cementation of a 1,000 year old oolite: Jour. Sed. Pet., v. 49, p. 969-988.


Harris, P. M., 1979, Facies anatomy and diagenesis of a Bahamian ooid shoal: Comparative Sedimentology Laboratory, Division of Marine Geology and Geophysics, Univ. of Miami, Miami, Florida.


Hazzard, R. T., Spooner, W. C., and Blanpied, B. W., 1947, Notes on the stratigraphy of the formations which underlie the Smackover Limestone in southern Arkansas, northeast Texas and northern Louisiana, in Reference report on certain oil and gas fields of northern Louisinna, southern Arkansas, Mississippi and Alabama: Shreveport Geol. Soc., v. 2, p. 483-503.


Rudolph, K., 1978, Diagenesis of backreef carbonates: an example from the Capitan complex: unpublished M.S., University of Texas, Austin, pp. 159.


Sigsby, R. J., 1976, Paleoenvironmental analysis of the Big Escambia Creek-Jay-Blackjack Creek Field area, Gulf Coast Assoc. Geol. Soc. Trans., v. 26, p. 258-278.


Stamatedes, M., 1982, Dolomitization of the Upper Smackover in Miller County, Arkansas and adjacent areas: unpublished M. S., Louisiana State University, Baton Rouge, Louisiana, pp. 164.


Tyrrell Jr., W. W., 1972, Denkman sandstone member - an important Jurassic reservoir in Mississippi, Alabama, and Florida: Gulf Coast Assoc. Geol. Soc. Trans., v. 22, p. 32.


Wilson, J. L., 1975, Carbonate Facies in Geologic History; Springer Verlag, New York, 471 pp.

APPENDIX A

ANALYTICAL METHODS
Thin Section Staining

The staining technique used is modified from Dickson (1966). Alizarin red S and potassium ferricyanide solids were dissolved in dilute hydrochloric acid. One liter of 0.5 percent HCl by volume was prepared. Four grams potassium ferricyanide and 0.6 grams alizarin red S were dissolved in 500 ml of the 0.5 percent HCl. This solution was then filtered. The remaining 500 ml of acid were used to etch the thin section prior to staining.

The intensity of the color depends on the length of time that the thin section is left in the stain. If differentiation of calcite and dolomite is desired, 45 seconds is a more than adequate staining time. Thin sections were prepared normally. The surface was only polished to the 5µm grit stage; if polished, the stain may peel off of the rock surface.

To stain the thin section, it was dipped into the 0.5 percent HCl for 10 seconds to clean the surface. The thin section was then dipped into stain for the desired time. It was necessary to agitate the thin section to prevent CO₂ bubbles from forming on the surface. The stained surface should not be touched because the stain rubs off easily. After the desired color developed, the thin section was washed in water and dried. The stained surface was coated with acetate to protect the surface and enhance light transmission for microscopy.

The stain reacts with carbonate minerals to produce the following colors:

Calcite................ pink to orange
Ferroan calcite........... purple-royal blue
Dolomite................. no stain

Ferroan dolomite.......... pale to deep turquoise or green

Sample Preparation - Anhydrite - Calcite Removal

The following procedure was used on selected dolomite samples for removal of anhydrite and calcite. The pure dolomite and insoluble residue which remained was split into two parts: one for chemical analysis by atomic absorption spectrophotometry (AAS) and the other for stable isotopic analysis. The techniques in this and the following section were developed by Dr. Eytan Sass.

The dolomite samples were powdered by hand in mortar and pestle til cohesive. Approximately 2 grams of powder was added to a 400 ml beaker for anhydrite treatment. Distilled water was added (350 ml) and stirred magnetically while conductivity was monitored for 15 minutes. At anhydrite saturation (achieved in 15 minutes) the conductivity is approximately 1.3 to 1.5 mmhos/cm. If the conductivity after 15 minutes remained low (0.5 mmhos/cm) anhydrite was gone, if not, the suspension was allowed to settle before decanting and repeating procedure. Once anhydrite was removed, beaker and contents were rinsed before treatment for calcite.

The minor amounts of calcite were removed by adding an excess (30 ml) of 0.5 N HCl. After thirty seconds, the beaker and contents were rinsed and the dolomite which remained was digested with 20 ml. of 5.0 N HCl for 30 minutes. This stock solution was filtered through number 40 filter paper into 100 ml volumetric flask. Insoluble residue was discarded.
Atomic Absorption

Stock was diluted to accommodate the range of the standards. Two milliliters of 15% KCl was added per 100 ml of final solution to buffer ionization effects for Sr$^{++}$ and Na$^+$ in the standards and the unknowns.

The measured amounts of Ca$^{++}$ and Mg$^{++}$ were used to calculate the mass of dolomite actually dissolved in the stock solution. It was upon this mass, not the original weight, that Sr$^{++}$ and Na$^+$ concentrations were calculated.

Concentrations of Ca$^{++}$, Mg$^{++}$, Sr$^{++}$ and Na$^+$ were determined using a varian AA-475 atomic absorption spectrophotometer. An air-acetylene flame was utilized in analyzing Ca$^{++}$, Mg$^{++}$ and Na$^+$. Nitrous oxide support was used in Sr$^{++}$ determinations to enhance absorbance.

Accuracy and reproducibility of the elemental analysis is based upon repeated analysis of National Bureau of Standards (NBS) reference sample 88a-dolomitic limestone. It should be noted that the NBS analysis of the standard dolomite 88a was carried out at least 15 years ago; the NBS values for trace elements were determined using methods that are less sensitive and precise than those used today (Cunningham, 1981).

The above techniques were used on 10 samples of NBS - 88a. Ten separate digestions and dilutions were run on two different days. The results are tabulated in Table B-1 (Appendix B) along with the weight percent values reported by NBS (1967). Of importance to this report is the high degree of precision. A comparison of means of 9-16 and 9-21 indicates greater variation exists from day to day than
among individual dilutions, however, reproducibility is still better than 1.0%.

The validity of accuracy (% error) must be questioned. The NBS analysis reports Ca, Mg, Sr and Na by whole rock analysis which involved digestion of carbonate and silicate material alike. Thus, it is unknown how much Sr and Na are contributed by the clay minerals.

The laboratory technique used in this study involved the removal of insoluble residue, which varied from 0 to 2 percent, from the stock solution. Therefore, contamination by the clay minerals is assumed to be minimal and comparison of the two sets of data for % error is inappropriate.

**X-Ray Diffraction**

The excess Ca$^{++}$ of the dolomite samples was determined by x-ray powder diffraction using a Philips XRG 3000 generator Philips ADP 3600 goniometer system. Ni-filtered, CuK radiation at a voltage of 40 KV and a current of 20 mA was used for crystallographic determinations.

The d-spacing of the dolomite crystals was determined by measuring the 2θ position of the (116,009) reflections (after Katz, 1971). The exact position of the (116) peak was measured relative to the (220) peak of a powdered fluorite internal standard. Five to 10% fluorite was mixed with each dolomite sample. A scanning rate of 0.01° 2θ per 4.72 seconds was used with a full scale of approximately 4000. This slow scan was run from 46.7° to 51.2° 2θ. Using the (116) peak position for the pure calcite-dolomite end members, a graph was constructed of changing (116) position versus mole percent
excess Ca$^{++}$. Although the true values deviate slightly from a straight line, this close approximation serves as a quality control to detect possible excessive Ca$^{++}$ contamination in the AAS analyses.

**Stable Isotope Analyses**

Carbon dioxide gas extracted from dolomite samples was analyzed for $^{13}$C and $^{18}$O by Dr. L. S. Land at the University of Texas, Austin and Dr. Pat Parker at Coastal Science Laboratories, Port Aransas, Texas. All values are relative to the PDB standard. Thirty-six samples analyzed by Pat Parker were shipped as pure dolomite powders, the pure dolomite being obtained by the method described in the section "sample preparation". Thirty-four samples of CO$_2$ gas were sent to Lynton Land for analysis. The CO$_2$ was extracted at LSU by Bill DeLoach according to the following procedure (DeLoach, personal communication):

1. Weigh out approximately 20 mg of sample, place in reaction vessel.
2. Measure out 10 ml 100% phosphoric acid, place in sidearm of reaction vessel.
3. Place reaction vessel on high vacuum gas extraction line; pump out air from vessel until it reaches high vacuum.
4. Close off reaction vessel, remove from high vacuum line and place in 25° (+0.5°) water bath for approximately 30 minutes.
5. After 30 minutes of equilibration invert reaction vessel to mix acid and sample.
6. Place vessel back into water bath and allow reaction to continue for approximately 24 hours.
7. After 24 hours, place reaction vessel on high vacuum extraction system. Collect CO$_2$ sample by freezing into sample tube.
8. Close off sample tube, allow to warm to room temperature. Remove sample tube from extraction line and place in shipping container.

Disguised powdered limestone from either the Solnhofen Limestone or NBS 88a were sent with each group of dolomite samples that were analyzed. Analyses of these samples were used to determine intra- and
inter-lab variation (Table B-5, Appendix B). Comparison of results from both labs shows that the inter-lab variation in $^{18}O$ values is within the limits of precision reported by each laboratory.

Cathodoluminescence

Cathodoluminescence is included because it is a useful method for examining zoning in cements. The geochemical information it provides is only qualitative. Standard petrographic thin sections were polished and then examined in a Nuclide ELM 2-B luminoscope using an accelerating voltage of 12 to 16 kV and beam current of 0.5 to 0.7 mA. Features were photographed using 6 to 10 minute exposure times.
APPENDIX D

ABBREVIATIONS AND SYMBOLS IN STRATIGRAPHIC SECTIONS

PLATES I-XV
Table D-1  Symbols used in maps and cross-sections (Plates I-XV).

<table>
<thead>
<tr>
<th>SYMBOLS</th>
<th>LITHOLOGY</th>
<th>FABRICS</th>
</tr>
</thead>
<tbody>
<tr>
<td>nodular mosaic anhydrite</td>
<td></td>
<td>grst-grainstone</td>
</tr>
<tr>
<td>ooids</td>
<td>limestone</td>
<td>pkst-packstone</td>
</tr>
<tr>
<td>unrecognizable grains</td>
<td>dolomite</td>
<td>wkst-wackestone</td>
</tr>
<tr>
<td>peloids</td>
<td>sandstone</td>
<td></td>
</tr>
<tr>
<td>oncolites</td>
<td>anhydrite</td>
<td>mudst-mudstone</td>
</tr>
<tr>
<td>bioclasts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>spicules</td>
<td></td>
<td></td>
</tr>
<tr>
<td>benthonic forams</td>
<td></td>
<td></td>
</tr>
<tr>
<td>echinoderms</td>
<td></td>
<td></td>
</tr>
<tr>
<td>anhydrite laths</td>
<td></td>
<td></td>
</tr>
<tr>
<td>blocky anhydrite</td>
<td></td>
<td></td>
</tr>
<tr>
<td>nodular anhydrite</td>
<td></td>
<td></td>
</tr>
<tr>
<td>burrows</td>
<td></td>
<td></td>
</tr>
<tr>
<td>whispy laminations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>stylolites</td>
<td></td>
<td></td>
</tr>
<tr>
<td>laminated bedding</td>
<td></td>
<td></td>
</tr>
<tr>
<td>cross bedding</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The following abbreviations were used on Plates I-VI for space saving purposes.

**Abbreviations**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>lm.</td>
<td>lime</td>
</tr>
<tr>
<td>anhy.</td>
<td>anhydrite</td>
</tr>
<tr>
<td>wkst.</td>
<td>wakestone</td>
</tr>
<tr>
<td>grst.</td>
<td>grainstone</td>
</tr>
<tr>
<td>ost.</td>
<td>ostracod</td>
</tr>
<tr>
<td>gast.</td>
<td>gastropod</td>
</tr>
<tr>
<td>onc.</td>
<td>oncolite</td>
</tr>
<tr>
<td>bur.</td>
<td>burrow</td>
</tr>
<tr>
<td>scat.</td>
<td>scattered</td>
</tr>
<tr>
<td>xline</td>
<td>crystalline</td>
</tr>
<tr>
<td>cem.</td>
<td>cement</td>
</tr>
<tr>
<td>nod.</td>
<td>nodular</td>
</tr>
<tr>
<td>flu.</td>
<td>fluorite</td>
</tr>
<tr>
<td>enc. bry.</td>
<td>encrusting bryozoa</td>
</tr>
<tr>
<td>mol. - th.sh.</td>
<td>mollusc - thin shelled</td>
</tr>
<tr>
<td>benth. foram</td>
<td>benthonic foraminifera</td>
</tr>
<tr>
<td>plank. foram</td>
<td>planktonic foraminifera</td>
</tr>
<tr>
<td>seg. algae</td>
<td>segmented algae</td>
</tr>
<tr>
<td>comp. lam.</td>
<td>compaction laminations</td>
</tr>
<tr>
<td>v.fn.gr.</td>
<td>very fine grained</td>
</tr>
<tr>
<td>Fe++ calsp.</td>
<td>ferroan calcpar</td>
</tr>
<tr>
<td>pseudo. gyp.</td>
<td>pseudomorph after gypsum</td>
</tr>
<tr>
<td>bk., dk. br., gy.</td>
<td>black, dark brown, gray</td>
</tr>
</tbody>
</table>

dolo. = dolomite
mudst. = mudstone
pkst. = packstone
0 = porosity
echin. = echinoderm
brach. = brachiopod
A/A = as above
tr. = trace
crs. = coarse
qtz. = quartz
poik. = poikilitic
cele. = celestite
Fav. sp. = Favreina sp.
mic. sty. = microstylolite
VITA

Marshall J. Vinet, son of Wilfred and Margaret Vinet, was born in New Orleans, Louisiana on the summer solstice of 1947. He was educated in the public school system and graduated from McDonough Senior High. He received his B.S. degree in Geology from the University of New Orleans in 1971 and his M.S. degree from the same school on December 19, 1975. He worked for Amoco Production Company in New Orleans from September of 1974 to May of 1978 at which time he began graduate work towards the PhD at Louisiana State University in Baton Rouge. He was gainfully employed at Davis Oil Company (presently Davis Petroleum Corp.) from May, 1982 to the summer of 1989. In November of 1989 he co-founded Pelican Oil and Gas Incorporated with partners Roy E. Lassus and Peter U. Schlegel.
Candidate: Marshall J. Vinet

Major Field: Geology

Title of Dissertation: Geochemistry and Origin of Smackover and Buckner Dolomites (Upper Jurassic), Jay Field Area, Alabama-Florida

Approved:

Major Professor and Chairman

Dean of the Graduate School

EXAMINING COMMITTEE:

Date of Examination:

April 17, 1990
PLATE III

EXXON #1 HART SEC 26, IN-8E ESCAMBIA, ALA.

Dry Hole

BUCKNER FM.

CORE ANALYSIS

LITH.

LITHOLOGIC DESCRIPTION

DEP. ENV.

DIAGENETIC FEATURES

REstricted, Subtidal, Below Wave Base Muds

LOWER SUBCONE.

UPPER SMACKOVER MEMBER

15,400

15,450

15,500

15,550
SUBTIDAL-BELOW WAVE BASE MUDS

RESTRICTED INNERTIDAL INNERSHELF SHALLOW LAGOON

LOWER SMACKOVER MEMBER

NORPHLET F.M.
RESTRICTED INNERSHELFD SHALLOW LAGOON

INNERSHELF SHALLOW LAGOON

- RESTRICTED
- MARGINAL MARINE-ALLUVIAL

- CHEMICAL ANALYSIS

M. J. VINET
EXXON #15 W. ST. REGIS SEC. 25, 4N-29W  SANTA ROSA, FLA.

Disposal Well-Blackjack Creek Field

PLATE VI

EXXON #15 W. ST. REGIS SEC. 25, 4N-29W  SANTA ROSA, FLA.

Disposal Well-Blackjack Creek Field

Chemical Analysis

M. J. VINET
PLEASE NOTE:

Oversize maps and charts are filmed in sections in the following manner:

LEFT TO RIGHT, TOP TO BOTTOM, WITH SMALL OVERLAPs

The following map or chart has been refilmed in its entirety at the end of this dissertation (not available on microfiche). A xerographic reproduction has been provided for paper copies and is inserted into the inside of the back cover.

Standard 35mm slides or 17” x 23” black and white photographic prints are available for an additional charge.
PLATE VII
STRUCTURAL MAP
TOP SMACKOVER FORMATION

M

B

I

A

T2N-R10E

T1N-R10H

CONECUH RIVER

BREWTON

NORTH RIVER
PLEASE NOTE:

Oversize maps and charts are filmed in sections in the following manner:

LEFT TO RIGHT, TOP TO BOTTOM, WITH SMALL OVERLAPS

The following map or chart has been refilmed in its entirety at the end of this dissertation (not available on microfiche). A xerographic reproduction has been provided for paper copies and is inserted into the inside of the back cover.

Standard 35mm slides or 17" x 23" black and white photographic prints are available for an additional charge.
PLEASE NOTE:

Oversize maps and charts are filmed in sections in the following manner:

LEFT TO RIGHT, TOP TO BOTTOM, WITH SMALL OVERLAPS

The following map or chart has been refilmed in its entirety at the end of this dissertation (not available on microfiche). A xerographic reproduction has been provided for paper copies and is inserted into the inside of the back cover.

Standard 35mm slides or 17" x 23" black and white photographic prints are available for an additional charge.
PLEASE NOTE:

Oversize maps and charts are filmed in sections in the following manner:

LEFT TO RIGHT, TOP TO BOTTOM, WITH SMALL OVERLAPS

The following map or chart has been refilmed in its entirety at the end of this dissertation (not available on microfiche). A xerographic reproduction has been provided for paper copies and is inserted into the inside of the back cover.

Standard 35mm slides or 17" x 23" black and white photographic prints are available for an additional charge.
PLEASE NOTE:

Oversize maps and charts are filmed in sections in the following manner:

LEFT TO RIGHT, TOP TO BOTTOM, WITH SMALL OVERLAPS

The following map or chart has been refilmed in its entirety at the end of this dissertation (not available on microfiche). A xerographic reproduction has been provided for paper copies and is inserted into the inside of the back cover.

Standard 35mm slides or 17" x 23" black and white photographic prints are available for an additional charge.
PLATE XI

NET POROSITY
SMACKOVER FORMATION
NET THICKNESS OF POROSITY = 10% OR GREATER

NOTE - Map is an estimation due to minor contour violations necessary to maintain general shapes.
PLEASE NOTE:

Oversize maps and charts are filmed in sections in the following manner:

LEFT TO RIGHT, TOP TO BOTTOM, WITH SMALL OVERLAPS

The following map or chart has been refilmed in its entirety at the end of this dissertation (not available on microfiche). A xerographic reproduction has been provided for paper copies and is inserted into the inside of the back cover.

Standard 35mm slides or 17" x 23" black and white photographic prints are available for an additional charge.
PLATE XII

STRATIGRAPHIC CROSS SECTION
B-B'

LEGEND

- MASSIVE ANHYDRITE
- ANHYDRITE NODULES
- GRAINSTONES (DOLOMITIZED)
- STUDY WELL
LOWER SMACKOVER
pellet-peloid packstones mostly dolomitized

NORPHLET
quartzarenite sands and gravel
PLEASE NOTE:

Oversize maps and charts are filmed in sections in the following manner:

**LEFT TO RIGHT, TOP TO BOTTOM, WITH SMALL OVERLAPS**

The following map or chart has been refilmed in its entirety at the end of this dissertation (not available on microfiche). A xerographic reproduction has been provided for paper copies and is inserted into the inside of the back cover.

Black and white photographic prints (17" x 23") are available for an additional charge.

University Microfilms International
Exxon
No. 1 Scott II-10
Sec. II, T1N - R7 E

Exxon
No. 1 McCurdy GU 12
Sec. 12, T1N - R7 E

Mallard
No. 1 Container of Am. 1-5
Sec. I, T1N - R7 E

SALT INTERVAL

LOWER SMACKOVER
pellet-peloid packstones mostly dolomitized

NORPHLET
quartzarenite sands and gravel

time pellet mudstones- wackestones
PLATE XIII
STRATIGRAPHIC CROSS SECTION C - C'

LEGEND

A MASSIVE ANHYDRITE
B ANHYDRITE NODULES
C GRAINSTONES (DOLOMITIZED)
D STUDY WELL
LOWER SMACKOVER
et-peloid packstones mostly dolomitized

NORPHLET
quartzarenite sands and gravel

SALT INTERVAL

lime pellet mudstones-wockeasters
PLEASE NOTE:

Oversize maps and charts are filmed in sections in the following manner:

LEFT TO RIGHT, TOP TO BOTTOM, WITH SMALL OVERLAPS

The following map or chart has been refilmed in its entirety at the end of this dissertation (not available on microfiche). A xerographic reproduction has been provided for paper copies and is inserted into the inside of the back cover.

Black and white photographic prints (17" x 23") are available for an additional charge.

University Microfilms International
Samedan
No. 1 Miller 10-1
Sec. 10, T 5 N - R 28 W

LEGEND

- MASSIVE ANHYDRITE
- ANHYDRITE NODULES
- GRAINSTONES (DOLOMITIZED)
- STUDY WELL

limestone pellet
muclstones - wackestones

mostly dolomitized
pellet-peloid packstones

STRATIGRAPHIC CROSS
D - D'

PLATE X
PLEASE NOTE:

Oversize maps and charts are filmed in sections in the following manner:

LEFT TO RIGHT, TOP TO BOTTOM, WITH SMALL OVERLAPS

The following map or chart has been refilmed in its entirety at the end of this dissertation (not available on microfiche). A xerographic reproduction has been provided for paper copies and is inserted into the inside of the back cover.

Standard 35mm slides or 17" x 23" black and white photographic prints are available for an additional charge.
Exxon
No. 1 Swift 10-5
sec.10, T5N - R29W

Gamma ray correlation (Detun)

calite-peloid grainstones
dolomite

pellet-peloid packstones mostly dolomitized

Santa Rosa County, Florida
Escambia County, Alabama

Exxon
No. 1 Bush 25-3
Sec. 25, T1N - R8E

Exxon
No. 1 Swift 10-5
sec.10, T5N - R29W
Tomlinson
No. 1 St. Regis 2-13
Sec. 2, T1N - R8E

Tesoro
No. 1 Huxford 27-11
Sec. 27, T2N - R9E

paleo-peloid packstones mostly dolomitized
pellet-peloid packstones mostly dolomitized
LEGEND

- MASSIVE ANHYDRITE
- ANHYDRITE NODULES
- GRAINSTONES (DOLomitized)
- STUDY WELL
PLATE XVI
(From Powell, 1984)

LEGEND

- OOID
- OCCUPIED OOD MOLD
- PELoids
- PELLET
- INTRAclAST
- GHOST OF GRAIN
- ONCoN
- MAJOR STYLOLITE
- ANHyDrite NODULE
- NODULAR MOSAIC ANHyDrite
- INTERLYERED MUDSTONE AND ANHyDrite

SCALE
HORIZONTAL: NONE
VERTICAL: 1' = 20'

BLE
BRAY
5,793'

HUMBLE
#5-4 HELMS
TD 16,110'

0.87 MILE
pellet-petrid pebbles mostly dolomited

pellet-pellet pebbles mostly dolomited

quartz wacke sand and gravel

NORPHLET

NORPHLET

siltite-siltite pebbles mostly dolomited

NORPHLET

siltite-siltite pebbles mostly dolomited

NORPHLET

NORPHLET

siltite-siltite pebbles mostly dolomited

siltite-siltite pebbles mostly dolomited

siltite-siltite pebbles mostly dolomited

siltite-siltite pebbles mostly dolomited

siltite-siltite pebbles mostly dolomited

siltite-siltite pebbles mostly dolomited

siltite-siltite pebbles mostly dolomited

siltite-siltite pebbles mostly dolomited