WELL-LOG SIGNATURES OF ALLUVIO-LACUSTRINE RESERVOIRS AND SOURCE ROCKS OF THE LAGOA FEIA FORMATION, LOWER CRETACEOUS, CAMPOS BASIN, OFFSHORE BRAZIL

by

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ABSTRACT

The Campos basin, offshore southeastern Brazil, has its geologic evolution linked to the Mesozoic rifting between Africa and South America. The Lagoa Feia is the synrift basal formation in the stratigraphic sequence of the basin, overlying and closely influenced by rift volcanics. It represents an evolving complex of lake basins laterally associated with alluvial fans. The sequence is dominated by lacustrine limestones and shales, some of them organic-rich, and volcaniclastic conglomerates. The organic-rich shales are the main source rocks within the Campos basin. Accumulations of coquinas are oil reservoirs in a restricted part of the formation. The entire sequence is capped by marine evaporites.

In the Lagoa Feia Formation, well-log interpretation is difficult because of the unique features associated with lacustrine deposits and with deposition during active tectonics. Complex lithologies, abrupt variation of facies, and unusual pore distributions in the reservoirs are the main factors to be considered in the application of traditional models of well-log interpretation. Effects of organic matter on well logs in organic-rich shales are detectable.
The unusual reservoir of coquinas correspond to levels of pure pelecypod shells with vuggy porosities. They are extremely heterogeneous in terms of porosity distributions and commonly present very high resistivities. Wettabilities may change towards oil-wet reservoirs at lower porosities. Silica cements are frequent. Water saturations calculated by the Archie equation are usually too optimistic. More realistic results were obtained in this study using increasing values of cementation and saturation exponents at lower porosities. Bulk volumes of water are extremely low, and water saturation maxima are only about 30% in intervals that produce oil.

The organic-rich lacustrine shales of the Lagoa Feia Formation show gamma-ray values lower than organic-rich marine shales, because of their lower uranium contents. Resistivity increases considerably only in mature source rocks. Laboratory measurements of TOC (total-organic-carbon contents) correlated with intervals of uniform readings on resistivity, sonic, density, neutron, and gamma-ray logs were treated statistically for the development of a model for the definition of important geochemical characteristics of the source rocks based on this well-log suite. Raw data of log readings were initially corrected for compaction. Discriminant analysis proved to be a very powerful
qualitative technique to discriminate between source rocks (TOC>2.0%) and lean ones (TOC<0.5%). Multiple regression generated a function that estimates TOC amounts that correlate with laboratory results, even on rocks with low TOC contents. Thicknesses of organic-rich beds and trends of variation in TOC amounts were better characterized through calibrated well-log readings than through scattered laboratory measurements. Ratios between resistivities of organic-rich shales and the interbedded lean shales are useful maturity indicators in this sequence, because type I kerogen is predominant, and, therefore, vitrinite particles are rare.

The results of this study indicate that models for well-log evaluation of source rocks are more effective if developed for each sequence of rocks covered by large databases. This procedure accounts for the mineralogic peculiarities of each sequence and for the statistical nature of well-log readings.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>iii</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>ix</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>xiv</td>
</tr>
<tr>
<td>LIST OF PLATES</td>
<td>xv</td>
</tr>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>xvi</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>PURPOSE AND SCOPE</td>
<td>6</td>
</tr>
<tr>
<td>Reservoir Rocks</td>
<td>7</td>
</tr>
<tr>
<td>Source Rocks</td>
<td>9</td>
</tr>
<tr>
<td>PREVIOUS WORK</td>
<td>11</td>
</tr>
<tr>
<td>Lagoa Feia Formation</td>
<td>12</td>
</tr>
<tr>
<td>Well-Log Analysis</td>
<td>14</td>
</tr>
<tr>
<td>Well-Log Responses of Source Rocks</td>
<td>22</td>
</tr>
<tr>
<td>APPROACH, DATABASE AND METHODS</td>
<td>27</td>
</tr>
<tr>
<td>Database</td>
<td>28</td>
</tr>
<tr>
<td>Geochemical Logs</td>
<td>31</td>
</tr>
<tr>
<td>Composite Logs</td>
<td>33</td>
</tr>
<tr>
<td>Methods</td>
<td>34</td>
</tr>
<tr>
<td>General Steps</td>
<td>34</td>
</tr>
<tr>
<td>Evaluation of the Reservoir Rocks</td>
<td>38</td>
</tr>
<tr>
<td>Evaluation of the Source Rocks</td>
<td>39</td>
</tr>
<tr>
<td>Software Utilized</td>
<td>43</td>
</tr>
<tr>
<td>ES-LOG</td>
<td>43</td>
</tr>
<tr>
<td>STATPAC</td>
<td>51</td>
</tr>
<tr>
<td>GEOLOGY.</td>
<td>52</td>
</tr>
<tr>
<td>The Lagoa Feia Formation in the Geologic</td>
<td>52</td>
</tr>
<tr>
<td>Evolution of the Campos Basin</td>
<td>52</td>
</tr>
<tr>
<td>Facies Assemblages</td>
<td>54</td>
</tr>
<tr>
<td>Alluvial Fans</td>
<td>55</td>
</tr>
<tr>
<td>Mud Flats</td>
<td>57</td>
</tr>
<tr>
<td>Lake Deposits</td>
<td>58</td>
</tr>
<tr>
<td>Age of Deposition</td>
<td>59</td>
</tr>
<tr>
<td>Summary of the Geologic Evolution</td>
<td>64</td>
</tr>
<tr>
<td>Similarities with the Recent</td>
<td></td>
</tr>
<tr>
<td>Lake Basins of East Africa</td>
<td>67</td>
</tr>
<tr>
<td>Section</td>
<td>Page</td>
</tr>
<tr>
<td>------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>WELL-LOG INTERPRETATION.</td>
<td>70</td>
</tr>
<tr>
<td>The Lower Portion</td>
<td>75</td>
</tr>
<tr>
<td>The Middle Portion</td>
<td>84</td>
</tr>
<tr>
<td>The Upper Portion</td>
<td>85</td>
</tr>
<tr>
<td>RESEVOIR ROCKS.</td>
<td>91</td>
</tr>
<tr>
<td>Well-Log Responses of Coquinas.</td>
<td>104</td>
</tr>
<tr>
<td>Definition of Parameters for the Evaluation</td>
<td>107</td>
</tr>
<tr>
<td>Lithology.</td>
<td>108</td>
</tr>
<tr>
<td>Porosity ((\phi))</td>
<td>111</td>
</tr>
<tr>
<td>Resistivity of Formation Water ((R_w))</td>
<td>117</td>
</tr>
<tr>
<td>True Resistivity of the Rock ((R_t))</td>
<td>119</td>
</tr>
<tr>
<td>Cementation Exponent ((m))</td>
<td>120</td>
</tr>
<tr>
<td>Saturation Exponent ((n))</td>
<td>124</td>
</tr>
<tr>
<td>Evaluation Approach</td>
<td>127</td>
</tr>
<tr>
<td>SOURCE ROCKS</td>
<td>141</td>
</tr>
<tr>
<td>Well-Log Responses of Organic Carbon</td>
<td>149</td>
</tr>
<tr>
<td>Database of Log Responses</td>
<td>154</td>
</tr>
<tr>
<td>Porosity Logs.</td>
<td>158</td>
</tr>
<tr>
<td>Gamma-Ray Logs.</td>
<td>165</td>
</tr>
<tr>
<td>Resistivity Logs.</td>
<td>173</td>
</tr>
<tr>
<td>Comparison with the Approach of Meyer and Nederlof.</td>
<td>175</td>
</tr>
<tr>
<td>Statistical Treatment of Data</td>
<td>179</td>
</tr>
<tr>
<td>Transformation of Data</td>
<td>180</td>
</tr>
<tr>
<td>Statistical Techniques</td>
<td>183</td>
</tr>
<tr>
<td>Discriminant Analysis</td>
<td>183</td>
</tr>
<tr>
<td>Multiple Regression</td>
<td>186</td>
</tr>
<tr>
<td>Application of Results</td>
<td>192</td>
</tr>
<tr>
<td>Cyclicality Supported by Well-Log Responses</td>
<td>200</td>
</tr>
<tr>
<td>Resistivity as Maturity Indicator</td>
<td>202</td>
</tr>
<tr>
<td>Final Results</td>
<td>210</td>
</tr>
<tr>
<td>CONCLUSIONS.</td>
<td>216</td>
</tr>
<tr>
<td>GLOSSARY</td>
<td>222</td>
</tr>
<tr>
<td>REFERENCES CITED</td>
<td>225</td>
</tr>
<tr>
<td>APPENDIX I - Additional Examples of Well-Log</td>
<td>238</td>
</tr>
<tr>
<td>Responses of Coquinas.</td>
<td></td>
</tr>
<tr>
<td>APPENDIX II - Additional Examples of Evaluation of Coquinas.</td>
<td>244</td>
</tr>
</tbody>
</table>
APPENDIX III - Additional Examples of Well-Log Responses of Source Rocks. .......... 250

APPENDIX IV - Additional Examples of Results Obtained in the Well-Log Evaluation of Source Rocks. 259

APPENDIX V - Database Used in this Study. .......... 268
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Geographic location of the Campos basin and some of its oil fields.</td>
<td>2</td>
</tr>
<tr>
<td>2.</td>
<td>Stratigraphy of the Campos basin.</td>
<td>3</td>
</tr>
<tr>
<td>3.</td>
<td>Summary of the database and location of the wells used in this study.</td>
<td>29</td>
</tr>
<tr>
<td>4.</td>
<td>Filtered data of well-log readings using ES-LOG</td>
<td>37</td>
</tr>
<tr>
<td>5.</td>
<td>Master and main menus of ES-LOG</td>
<td>45</td>
</tr>
<tr>
<td>6.</td>
<td>Menu for the execution of a Pickett plot using ES-LOG</td>
<td>47</td>
</tr>
<tr>
<td>7.</td>
<td>Schematic stratigraphic cross sections along two perpendicular directions in the Campos basin.</td>
<td>56</td>
</tr>
<tr>
<td>8.</td>
<td>Schematic distribution of depositional environments</td>
<td>60</td>
</tr>
<tr>
<td>9.</td>
<td>Chronostratigraphic subdivisions for the Lagoa Feia sediments.</td>
<td>63</td>
</tr>
<tr>
<td>10.</td>
<td>Schematic stages of evolution</td>
<td>65</td>
</tr>
<tr>
<td>11.</td>
<td>Composite stratigraphic column of the Lagoa Feia Formation.</td>
<td>74</td>
</tr>
<tr>
<td>12.</td>
<td>Oolites of stevensite (photo)</td>
<td>77</td>
</tr>
<tr>
<td>13.</td>
<td>Oolites of stevensite (photomicrograph)</td>
<td>78</td>
</tr>
<tr>
<td>14.</td>
<td>Well-log responses in the lower portion</td>
<td>79</td>
</tr>
<tr>
<td>15.</td>
<td>Oolites of stevensite from the Green River Formation (photomicrograph)</td>
<td>82</td>
</tr>
<tr>
<td>16.</td>
<td>Oolites of stevensite under plain light (photomicrograph)</td>
<td>83</td>
</tr>
<tr>
<td>17.</td>
<td>Volcaniclastic conglomerate (photo)</td>
<td>86</td>
</tr>
<tr>
<td>18.</td>
<td>Well-log responses in the upper portion</td>
<td>87</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Page</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>------</td>
</tr>
<tr>
<td>19</td>
<td>Volcaniclastic conglomerate (photomicrograph)</td>
<td>90</td>
</tr>
<tr>
<td>20</td>
<td>Coquina reservoir (photo)</td>
<td>92</td>
</tr>
<tr>
<td>21</td>
<td>Porosity-permeability relationships existing in the coquinas.</td>
<td>94</td>
</tr>
<tr>
<td>22</td>
<td>Early cementation effects on coquinas (photomicrographs)</td>
<td>96</td>
</tr>
<tr>
<td>23</td>
<td>Ostracode-rich coquina (photomicrograph)</td>
<td>99</td>
</tr>
<tr>
<td>24</td>
<td>Silica cements (photomicrographs)</td>
<td>100</td>
</tr>
<tr>
<td>25</td>
<td>Effects of pH on the solubility of silica</td>
<td>103</td>
</tr>
<tr>
<td>26</td>
<td>Common well-log responses of coquina reservoirs</td>
<td>105</td>
</tr>
<tr>
<td>27</td>
<td>Neutron-density porosity crossplot</td>
<td>109</td>
</tr>
<tr>
<td>28</td>
<td>Porosity crossplot for high-porosity coquina</td>
<td>112</td>
</tr>
<tr>
<td>29</td>
<td>Porosity crossplot for low-porosity coquina</td>
<td>113</td>
</tr>
<tr>
<td>30</td>
<td>&quot;Secondary&quot; porosities of coquinas</td>
<td>116</td>
</tr>
<tr>
<td>31</td>
<td>Definition of Rw values for the coquina reservoirs</td>
<td>118</td>
</tr>
<tr>
<td>32</td>
<td>Measured values of m versus vug porosity ratios</td>
<td>122</td>
</tr>
<tr>
<td>33</td>
<td>Overall characteristics of a Pickett plot</td>
<td>123</td>
</tr>
<tr>
<td>34</td>
<td>Pickett plot of coquina reservoirs</td>
<td>125</td>
</tr>
<tr>
<td>35</td>
<td>Pickett plot of oil-producing coquinas</td>
<td>130</td>
</tr>
<tr>
<td>36</td>
<td>Resistivity formation factor versus porosity</td>
<td>132</td>
</tr>
<tr>
<td>37</td>
<td>Behavior of coquinas in irreducible-water zones</td>
<td>134</td>
</tr>
<tr>
<td>38</td>
<td>Final evaluation obtained for the coquina reservoirs</td>
<td>136</td>
</tr>
<tr>
<td>39</td>
<td>Typical shale of the Lagoa Feia Formation (photo)</td>
<td>142</td>
</tr>
<tr>
<td>40</td>
<td>Black, organic-rich shale (photo)</td>
<td>143</td>
</tr>
<tr>
<td>Chapter</td>
<td>Title</td>
<td>Page</td>
</tr>
<tr>
<td>---------</td>
<td>-----------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>41</td>
<td>Organic-rich shales (photomicrographs)</td>
<td>144</td>
</tr>
<tr>
<td>42</td>
<td>Well-log responses of shales</td>
<td>155</td>
</tr>
<tr>
<td>43</td>
<td>Density porosities of shales</td>
<td>160</td>
</tr>
<tr>
<td>44</td>
<td>Sonic porosities of shales</td>
<td>161</td>
</tr>
<tr>
<td>45</td>
<td>Neutron porosities of shales</td>
<td>162</td>
</tr>
<tr>
<td>46</td>
<td>Differences on relative porosities from neutron and density logs</td>
<td>164</td>
</tr>
<tr>
<td>47</td>
<td>$\phi_n - \phi_d$ values for lean and organic-rich shales</td>
<td>166</td>
</tr>
<tr>
<td>48</td>
<td>Gamma-ray values of lean and organic-rich shales</td>
<td>167</td>
</tr>
<tr>
<td>49</td>
<td>Comparison of gamma-ray responses in the Lagoa Feia and in the Bakken Formations</td>
<td>170</td>
</tr>
<tr>
<td>50</td>
<td>Resistivity values of shales</td>
<td>174</td>
</tr>
<tr>
<td>51</td>
<td>Results obtained by Meyer and Nederlof</td>
<td>176</td>
</tr>
<tr>
<td>52</td>
<td>Meyer and Nederlof approach applied on shales of the Lagoa Feia Formation</td>
<td>178</td>
</tr>
<tr>
<td>53</td>
<td>Distributions of raw data of density, sonic and TOC values of shales</td>
<td>181</td>
</tr>
<tr>
<td>54</td>
<td>Distribution of variables after transformations</td>
<td>184</td>
</tr>
<tr>
<td>55</td>
<td>Results of discriminant analysis</td>
<td>187</td>
</tr>
<tr>
<td>56</td>
<td>Prediction of TOC values obtained through multiple regression</td>
<td>191</td>
</tr>
<tr>
<td>57</td>
<td>Examples of results obtained after entering the multiple regression and discriminant functions into ES-LOG</td>
<td>193</td>
</tr>
<tr>
<td>58</td>
<td>Comparison of different vertical resolutions of cores, logs, and seismic sections</td>
<td>194</td>
</tr>
<tr>
<td>59</td>
<td>Variation in amounts of organic carbon in different laminae of shales (photomicrograph)</td>
<td>197</td>
</tr>
</tbody>
</table>
60. Comparison of log results with laboratory data...
61. Cycliclicity observed in the results
62. Resistivity increase due to maturity of the source rock
63. Vitrinite reflectance versus resistivity ratios
64. Kerogen types in the Lagoa Feia Formation
65. $T_{\text{max}}$ responses for different kerogen types
66. $T_{\text{max}}$ values in the Lagoa Feia Formation
67. Association of results from discriminant analysis and multiple regression with resistivity values
68. Additional example of log responses of coquinas
69. Additional example of log responses of coquinas
70. Additional example of log responses of coquinas
71. Additional example of log responses of coquinas
72. Additional example of log responses of coquinas
73. Evaluation results obtained for coquinas presented on Figure 68.
74. Evaluation results obtained for coquinas presented on Figure 69.
75. Evaluation results obtained for coquinas presented on Figure 70.
76. Evaluation results obtained for coquinas presented on Figure 71.
77. Evaluation results obtained for coquinas presented on Figure 72.
78. Additional example of log responses of shales
79. Additional example of log responses of shales
<table>
<thead>
<tr>
<th>80.</th>
<th>Additional example of log responses of shales</th>
<th>253</th>
</tr>
</thead>
<tbody>
<tr>
<td>81.</td>
<td>Additional example of log responses of shales</td>
<td>254</td>
</tr>
<tr>
<td>82.</td>
<td>Additional example of log responses of shales</td>
<td>255</td>
</tr>
<tr>
<td>83.</td>
<td>Additional example of log responses of shales</td>
<td>256</td>
</tr>
<tr>
<td>84.</td>
<td>Additional example of log responses of shales</td>
<td>257</td>
</tr>
<tr>
<td>85.</td>
<td>Additional example of log responses of shales</td>
<td>258</td>
</tr>
<tr>
<td>86.</td>
<td>Well-log, source-rock potential results obtained for shales presented on Figure 78.</td>
<td>260</td>
</tr>
<tr>
<td>87.</td>
<td>Well-log, source-rock potential results obtained for shales presented on Figure 79.</td>
<td>261</td>
</tr>
<tr>
<td>88.</td>
<td>Well-log, source-rock potential results obtained for shales presented on Figure 80.</td>
<td>262</td>
</tr>
<tr>
<td>89.</td>
<td>Well-log, source-rock potential results obtained for shales presented on Figure 81.</td>
<td>263</td>
</tr>
<tr>
<td>90.</td>
<td>Well-log, source-rock potential results obtained for shales presented on Figure 82.</td>
<td>264</td>
</tr>
<tr>
<td>91.</td>
<td>Well-log, source-rock potential results obtained for shales presented on Figure 83.</td>
<td>265</td>
</tr>
<tr>
<td>92.</td>
<td>Well-log, source-rock potential results obtained for shales presented on Figure 84.</td>
<td>266</td>
</tr>
<tr>
<td>93.</td>
<td>Additional example of well-log, source-rock potential results obtained for lacustrine shales.</td>
<td>267</td>
</tr>
</tbody>
</table>
T-3589

LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table I</td>
<td>Procedures to be followed in the well-log evaluation of coquina reservoirs</td>
<td>137</td>
</tr>
<tr>
<td>Table II</td>
<td>Standardized Regression Coefficients.</td>
<td>190</td>
</tr>
<tr>
<td>Table III</td>
<td>Procedures to be followed in the well-log evaluation of source rocks</td>
<td>213</td>
</tr>
</tbody>
</table>
LIST OF PLATES*

Plate I - Example of a geochemical log used in this study

Plate II - Example of a Z-plot generated using ES-LOG

Plate III - Example of a Quad-plot generated using ES-LOG

Plate IV - Example of results in the evaluation of the coquinas

Plate V - Example of the evaluation of source-rock potential in the sequence

* Plates are in the pocket in the back of the thesis.
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INTRODUCTION

The Campos basin (Fig. 1) is located in southeastern Brazil, on the northern coast of the state of Rio de Janeiro, between the latitudes of 21° 30' and 23° 30' S, and the longitudes of 40° 15' and 41° 30' W. The basin is mainly offshore and occupies an area of 32,500 km² up to the 1,000 m isobath. The Campos basin, like all the other marginal Brazilian basins, has its geologic evolution connected to the Mesozoic rifting between Africa and South America. Since the first oil discovery in the basin in 1974, several other oil fields were discovered, transforming this basin into the most prolific in Brazil. The Campos basin produces today more than 60% of the daily oil production in the country, which is about 600,000 bbl of oil.

The Lower Cretaceous Lagoa Feia, the basal formation in the stratigraphic sequence of the Campos basin (Fig. 2), was deposited during rifting approximately between 125 and 106 Ma. Only four oil fields produce from reservoirs within the Lagoa Feia Formation (see Fig. 1). However, the only mature source rocks known in the whole sequence of the basin are the organic-rich lacustrine shales of this formation. The Lagoa Feia Formation has been penetrated in more than
Figure 1. Geographic location of the Campos basin and some of its oil fields. In solid black are fields that produce from the Lagoa Feia Formation, which are located in the Badejo High area. Subdivisions on vertical and horizontal borders of the figure represent values of X (between 7.35 and $7.65 \times 10^6$ m) and Y (between 225 and $400 \times 10^3$ m) in UTM coordinates related to the central meridian of $39^\circ$. 
Figure 2. Stratigraphy of the Campos basin showing the Lagoa Feia as the basal formation, above the basaltic basement and underneath the marine carbonates of the Macaé Formation (from Petrobrás/SECASU, unpublished internal report).
one third of the wells in the Campos basin, in a range of depths varying between about 1,800 and 5,200 m. It averages 800 m in thickness. Until now, a maximum of 1,400 m of it has been drilled, although from seismic data the sequence may reach up to 4,000 m in thickness in the deeper portions of the basin.

A mosaic of facies, deposited in alluvial fans, mud flats, and lakes, forms the geologic record of the Lagoa Feia Formation. There is a remarkable association with rift volcanics, especially in the basal portion of the unit. The best analog for this depositional sequence is encountered in the depositional environments occurring in the recent lake basins associated with the East African rift system (Abrahão, 1987).

Because of the unique characteristics of the Lagoa Feia lake deposits, well-log interpretation in this alluvio-lacustrine sequence is difficult, mostly because of:

a) unusual mineralologic constituents,
b) unconventional reservoirs of coquina, and
c) high sensitivity to climate variations and tectonism during deposition, both factors creating abrupt changes in facies and vertical and horizontal discontinuities in the sequence.

In this research, the emphasis is on the well-log
characterization of geological data within this complex rock sequence, and its application to petroleum exploration. A model for the evaluation of the coquina reservoirs is outlined, and a method for characterization of important geochemical properties of the lacustrine shales is developed, both through well-log responses.
PURPOSE AND SCOPE

This thesis research is a petroleum geology study based on subsurface data. The resolution of well logs in the definition of geologic, petrophysical, and geochemical characteristics, of both reservoirs and source rocks, has been investigated by many authors. Formation evaluation through well logs is an area where new approaches and theories are continuously developing. In this respect, studies that consider geological information are always more appropriate than the ones that just handle engineering rock parameters. In parallel, the use of the computer has a tremendous potential to transform measurements of modern logging tools into continuous profiles of geological variability which can express lithofacies, mineralogy, internal geometry, and other important geological information of rock sequences.

The use of well logs is appropriate in the study of the subsurface because logs are continuous records of indirect measurements in wells and can give precise information about the location of specific intervals and trends of variation of particular characteristics. On the other hand, the definition of well-log characteristics of rocks, relative to small-scale geologic features, often cannot be compared to
that obtained through core descriptions. Nevertheless
direct measurements made continuously on cores from a well,
although accurate, are costly. If these measurements are
made on cuttings, the apparent depths they come from have to
be adjusted. In addition, the existence of overlaps in
parallel to the selective preservation of cuttings, create
additional problems. So, it is preferable to calibrate
well-log responses with rock properties observed or measured
in cores and cuttings. This procedure increases the
resolution of the well-logs and makes them more valuable for
geological studies based on subsurface data.

In the Lagoa Feia Formation, several parameters can be
derived from well logs for the unconventional coquina
reservoirs and for the organic-rich lacustrine shales. This
study is divided into two main parts; one that covers the
well-log signatures of the coquina reservoirs, and the other
that involves well-log responses of the source rocks of the
Lagoa Feia Formation.

**Reservoir Rocks**

Relative to the coquina reservoirs, the main purpose of
this study is to analyze in detail their overall features
and arrive at a better understanding of how the reservoir characteristics of these rocks can be defined through well-log readings. The main objective is to increase the resolution of the well logs, generating more information in areas or intervals where the section was not cored or the wells were not tested.

The traditional Archie method of well-log interpretation, may produce poor results when applied without compensating for their peculiar characteristics. The existence of vuggy porosities and occurrence of complex lithologies, connected mostly with diagenetic effects, commonly create problems in the characterization of fluid saturations in most of the wells. To solve this problem, data from the description of cores, thin sections, and well-testing operations are compared to well-log signatures in order to characterize reservoir parameters. New approaches are developed for the derivation of petrophysical parameters of these reservoirs using well logs.

The ultimate goal is to develop an interpretive model of well-log evaluation to forecast more accurately the reservoir fluids in the coquinas and the productivity potential of different intervals.
Source Rocks

Regarding the source rocks, earlier studies in the Campos basin have recognized their existence in the stratigraphic sequence of the Lagoa Feia Formation. Those studies have shown that these organic-rich rocks were the source of oil for all the reservoirs discovered to date in the Campos basin, both within and above the Lagoa Feia Formation. However, none of these studies has characterized the variations in quality of these rocks, as well as their areal distribution.

The definition of geochemical data in organic-rich rocks through well logs is possible. Depending on the amount of organic material in potential source rocks, geophysical wireline responses can be significantly affected due to the distinctive physical properties of organic carbon in relation to the matrix of shales and carbonates (Fertl, Chilingar, and Yen, 1986). In parallel, the presence of oil in the interstices of rocks mature enough to generate hydrocarbons usually gives higher readings on resistivity logs.

The source rocks in the Lagoa Feia Formation are very rich in some levels and may allow the definition of their geochemical properties through well logs. Some results of
well-logging responses on source rocks are presented in the literature for a few American and European basins (see next section on previous work).

In this study, the comparison of data from geochemical analyses with well-log responses is performed in order to characterize the most important geochemical parameters of the sequence through a detailed analysis of well-log readings. The main purpose is the definition of how well logs can help in the derivation of information about the richness, maturity level, and thickness of source rocks within the Lagoa Feia Formation, especially in areas or intervals where geochemical analyses are not available. A database for future use in volumetric calculations for prospective areas is created.

Multivariate statistical techniques applied to well-log readings are used in this research to develop models for evaluating the source rocks within the sequence. The target is to develop a model to assess the source-rock potential of the lacustrine shales from well-log readings, which will work as a complement for the expensive geochemical measurements obtained in laboratory.
PREVIOUS WORK

Marginal Brazilian basins have been mostly studied after the mid 70's because of the conjunction of the following factors:

a) decline of discoveries and of potential in older onshore productive areas like the Reconcavo and the Sergipe/Alagoas basins,
b) the necessity to intensify the exploration activities because of increasing industrial consumption in the country,
c) drilling offshore, starting in 1968, with some good discoveries,
d) better comprehension of the geological factors involved in the evolution of these basins, in parallel with the evolution of the concepts of plate tectonics theory.

Good syntheses discussing the Brazilian marginal basins were performed by Campos et al. (1974) and Ojeda (1982), among others.

Well-log analysis, on the other hand, has been a very important research area in the oil industry since the early 40's. During the past four decades, most papers that address the evaluation of reservoir rocks used deterministic
approaches to define engineering parameters for these rocks. Recently, a more geologic approach to log analysis has been adopted, in parallel with the development of modern and more sophisticated logging tools.

The statistical nature of well-log responses has been recognized by several authors. The advantages of a statistical approach to log analysis have been extensively discussed. Statistical techniques use "inverse" methods to calculate formation parameters (Mitchell and Nelson, 1988). However, in the main, log analysts still tackle the task of extracting relevant information from log data as if in the deterministic environment (Moss and Harrison, 1986).

Characterization of source rocks using well logs started only after major developments in petroleum geochemistry that occurred in the late 70’s. Therefore, most of the papers discussing this subject appeared in the literature only during this last decade.

**Lagoa Feia Formation**

The stratigraphy of the Campos basin was initially defined by Schaller (1973), using information from the first wells drilled in the basin. Other geologic studies in the
Lagoa Feia Formation, involving the areas close to the oil fields discovered in this formation (see Fig. 1), were performed by Castro and Azambuja (1980), Schaller et al. (1981), Ojeda (1983), and Baumgarten (1983, 1985).

Pereira (1980) identified the initial problems encountered in the well-log evaluation of coquina reservoirs within the Lagoa Feia Formation. Pereira (1982) applied the Lopatin’s method (Waples, 1985) to the sedimentary sequence of the Campos basin and concluded that the only significant source rocks mature enough for oil generation in the basin belong to the Lagoa Feia Formation.

Using data from 27 wells in the Badejo High area (see Fig. 1), Bertani (1984) and Bertani and Carozzi (1985a, 1985b) addressed mainly the diagenetic aspects affecting the reservoir rocks in the stratigraphic sequence of the Lagoa Feia Formation. Other comprehensive studies, using more data that became available and involving mostly diagenesis in these same reservoir rocks, were conducted by Carvalho et al. (1984), and Carvalho, Monteiro, and Misuzaki (1985). These studies utilized data from 66 wells, again close to the Badejo High oil fields. More recent studies defining the oil habitats existing in the Campos basin, and associating them with source rocks within the Lagoa Feia Formation, were performed by Meister (1984), Figueiredo et
al. (1985), and Pereira, Trindade and Gaglianone (1985).

In the most recent study of the Lagoa Feia Formation, the distribution of facies and the geologic evolution of the unit were shown in the form of a regional study, based on data from 137 wells. In this study, generalized exploration ideas for the stratigraphic sequence of the Lagoa Feia Formation in the Campos basin were also developed (Abrahão, 1987).

Well-Log Analysis

Subsurface reservoir rocks have been studied through well logs, especially by petroleum engineers. These studies started with Archie (1942), in an empirical approach where the basis for the characterization of fluids and productivity of reservoir rocks through well-log readings was established. Since then, numerous papers have been published where reservoir characterization is discussed through well-log responses. Archie's approach, with modifications introduced by more recent studies, is still valid. The Archie equation, defined initially for sandstone reservoirs, is represented by:
\[ Sw = \sqrt[n]{\frac{F \cdot Rw}{Rt}} \]

where \( F = \frac{Ro}{Rw} \), or in an equivalent expression, \( F = \phi^{-m} \),

\( \phi \) = porosity fraction of the rock,

\( m \) = cementation exponent,

\( n \) = saturation exponent,

\( Sw \) = interstitial water saturation,

\( Rw \) = resistivity of formation water (or connate water),

\( Ro \) = resistivity of the rock completely saturated by water, and

\( Rt \) = true resistivity of the formation.

The parameter \( F \) is known as the resistivity formation factor of the rock, and it is a fundamental parameter in the definition of the water saturation of a reservoir rock. A modified expression for \( F \), \( F = a\phi^{-m} \), appeared later in the literature. Although the coefficient "a" was initially described as a conductivity coefficient (Winsauer et al., 1952), or it is sometimes attributed to represent effects of tortuosity or compaction of the reservoir rocks, in the opinion of some authors it has no relation to a property of rock or water (Ransom, 1974).

In a study relating well-log data to core descriptions,
Archie (1952) discussed the definition of petrophysical properties in carbonates, in a period when porosity wireline tools (namely density, sonic, and neutron) were not yet available. In that paper, he recognized the difficulties of making well-log interpretation in carbonates, due to their heterogeneities when compared to sandstones, and created a classification for these rocks based on their pore-size distributions. Chombart (1960) went further in the recognition of the extraordinary heterogeneity of carbonate reservoirs and established the necessity to define relationships between pore-size distribution, porosity, and water saturation based on statistics. For these earlier papers the well-log data available were from older tools. However, all of these approaches are still valid, even with the larger amount and higher quality of well-log data available today from modern tools.

Although Hingle (1959) initially showed the use of crossplots of resistivities versus porosities from well-log measurements in the evaluation of reservoirs, it was Pickett (1966) who better demonstrated the usefulness of these crossplots in the definition of water saturations in intervals where uncertainties exist mainly in formation water resistivities (Rw) and cementation exponents (m). Pickett plots are still fundamental in well-log evaluation.
of hydrocarbon-bearing reservoirs.

Clay effects on resistivity data, and consequently on well-log evaluation of reservoir rocks, were noticed as early as 1950. Nevertheless, this problem only started to be better understood close to the end of the 60's when Waxman and Smits (1968) developed a model to evaluate reservoirs by compensating for the cation exchange capacity of the shale fraction present in these rocks.

Carothers (1968) performed a complete statistical study of measured resistivity formation factors using almost 1,000 of these measurements obtained in laboratory. He defined precise relationships between resistivity formation factors and porosity, valid for most sandstones and carbonates. Porter, Pickett, and Whitman (1969), appreciating the statistical nature of well-log measurements, introduced a statistical method for the detection of hydrocarbons in intervals where uncertainties exist about the parameters necessary to solve the Archie equation.

The availability of new tools, and consequently new parameters measured by well logs, increased the capacity for resolving problems of reservoir evaluation in the subsurface. Gaymard and Poupon (1968) introduced the methods of evaluation of reservoir parameters, such as: lithology, porosity, and fluid saturations, through the use
of density-neutron log combinations.

Porter and Carothers (1970) defined the resistivity formation factor-porosity relations existing in 2295 samples from the Pliocene of California and the Miocene of Texas-Louisiana. They concluded that reliable resistivity formation factor-porosity relations can be defined using well-log data, and that care should be exercised in the transfer of these relations from one geological province to another.

The use of computers transformed the previously tedious calculations, and in some cases impossible-to-apply methods, into useful techniques for the continuous definition of rock properties. This approach was very well illustrated by Poupon, Hoyle, and Schmidt (1971), in their computerized evaluation method for "complex lithologies" using complete suites of logs including gamma-ray, density, neutron, sonic, and resistivity logs.

Pickett (1973) readressed the question of using cross-plotting techniques in reservoir evaluation and derived techniques for interpreting patterns obtained from the possible cross-plot responses. He showed that the appropriate cross-plot of resistivity versus porosity leads to a geometric pattern of data points which can be analyzed to obtain estimates of water saturation without the
knowledge of porosity, m, or Rw, with the circumvention of problems of miscalibration of porosity and resistivity logs. A limitation of the method, however, is the necessity of a statistically significant number of zones with reasonably constant values of m and Rw.

Clavier, Coates, and Dumanoir (1977) further developed the Waxman-Smits model for the evaluation of shaly sands introducing the dual-water model. This model is still the better approach for the evaluation of shaly reservoirs, although the shaly sand problem has not yet received a completely satisfactory solution (Worthington, 1985).

The use of the computer in the treatment of well-log data in order to generate reservoir evaluation and geologic information, taking into account the statistical nature of well-log readings, led to the development of the GLOBAL software (Mayer and Sibbit, 1981). This software integrates well-log information to solve geologic problems in sequences involving several kinds of mineralogic constituents. Furthermore, the FACIOLOG software (Wolf and Pelissier-Combescure, 1982), through a technique of cluster analysis, automatically defines electro-facies from combined well-log readings, in a very geologic approach.

Etnyre (1982) went further in the statistical detection of hydrocarbons from well logs using the same approach of
Porter, Pickett, and Whitman (1969), adjusting it for dealing with small amounts of data. Lucia (1983) studied the behavior of cementation exponents (m) in carbonates with vuggy porosities and provided a technique in which m values and permeabilities can be estimated from the calibration of laboratory data with wireline-log readings. Rasmus (1983) in a sturdy supported by both core and production data, showed the variation of m exponents in fractured carbonates.

In a series of pitfalls in log analysis, Elliott (1983) showed that it is wrong to assume that low water saturations, defined through well-log evaluation, will always imply production of water-free hydrocarbons and vice-versa. Ransom (1984) gave a better physical definition for the parameters a, m, and n existing in Archie's equation. Hilchie (1984) showed the state-of-the-art in reservoir description through well logs. He presented the approaches in the analysis of modern-tool readings in the definition of depth, thickness, porosity, pore sizes, water saturation, fluid type, grain sizes, depositional environments, and lithology within rock sequences.

Moss and Harrison (1986) presented a detailed analysis of the statistical nature of well-log measurements and discussed statistical techniques that can lead the log analyst to maximize the information that may be obtained
from well logs, and, consequently, to a better understanding of the formations of interest. They stated that they have never met any data-analysis problems, outside the laboratory, which are deterministic. They went further saying that by refusing to accept the existence of errors in collecting log data and by assuming that the log response equations are perfect predictors, log analysts have made their task unnecessarily complicated. In addition, they affirmed that the deterministic approaches are unable to extract all the information available in the data.

Whitman (1986) presented a technique for weighting the information, based on previously known geologic conditions, that leads to better results in the evaluation of reservoirs through the use of Pickett plots. King and Quirein (1986) showed a technique for modelling geologic data through the statistical treatment of well-log readings in a more precise definition of electrofacies. Baker (1987) is currently developing the same kind of approach to come up with a more reliable technique for the interpretation of facies from well-log data.

Rasmus (1987) developed mathematical models for the relationships of \( m \) and \( n \) in fracture- and vuggy-porosity carbonates. Mitchell and Nelson (1988) are going further in the statistical approach in log analysis showing the
advantages of such approaches.

In the last four decades, much progress was attained in the area of well-log interpretation. In recent years there has been a steady evolution within log analysis from methods grounded firmly in classical reservoir engineering theory to a more integrated approach, which incorporates geological concepts and interpretations (Doveton, 1986). The way is still open for further investigation into the extraction of a maximum of geologic information from well logs associated with other subsurface data.

Well-Log Responses of Source Rocks

Although studies relating the yield potential of oil shales with responses in the density logs were performed by Tixier and Curtis (1967) and Smith, Thomas, and Trudell (1968), the age of source-rock evaluation through well logs started with Meissner (1978). He defined geochemical characteristics of the shales existing in the Bakken Formation, Williston basin, from log readings in the gamma-ray, sonic, and resistivity logs. More or less in the same period, Schmoker (1979) determined the organic content of the Devonian shales of the Appalachian basin using density logs, and later performed a similar study in the same rocks
using gamma-ray logs (Schmoker, 1981).

Dellenbach, Espitalie, and Lebreton (1983), using sonic, resistivity, and gamma-ray logs, studied the source rocks existing in the Paris basin. Schmoker and Hester (1983) studied the organic content of shales in the Bakken Formation using density logs.

Meyer and Nederlof (1984, 1986; Aljawadi, 1986) presented a technique for evaluating source rocks, to be used worldwide, based on crossplotting techniques over readings of the density, sonic, and resistivity logs. Their results were calibrated with 169 samples from nine basins around the world, all of them from marine source rocks.


Mendelson (1985) presented a theoretical approach for the evaluation of source rocks from well-log readings, whereas Mendelson and Toksöz (1985) used statistical techniques on readings from gamma-ray, resistivity, density, sonic, and neutron logs to compute the organic content of rocks from the Kimmeridge and Monterey Formations. They
concluded that although multivariate regression significantly improves the ability to predict TOC (total organic carbon) within each dataset, there are no similarities among the equations, so success of prediction over new data would be sporadic.

Chilingar, Fertl, and Yen (1985) presented a way of classifying source rocks in the Gulf Coast using resistivity logs. Fertl and Chilingar (1986), and Fertl, Chilingar, and Yen (1986) presented a complete theoretical approach for the detection of organic carbon in all kinds of logs available at that time, using some examples from the literature presented by previous authors.

Mann, Leythaeuser, and Müller (1986) studied the well-log responses of the Lower Jurassic Posidonia Shale in northwest Germany and concluded that only the uranium content, defined through the spectral gamma-ray log, was a good indicator of organic carbon contents in that marine rock sequence, whereas density, sonic, and resistivity logs did not provide useful data, in this regard.

Hester and Schmoker (1987), again using density logs, defined a method for the derivation of organic contents in the Devonian-Mississipian Woodford Shale of the Anadarko basin.

Herron (1986, 1987) presented the measurements of TOC
amounts that can be derived from direct measurements of induced gamma-ray spectra. Grau and Herron (1987) presented a more sophisticated spectrometry tool with higher chances of success in the definition not only of the source-rock potential but also of a more complete mineralogic characterization of rock sequences, including unusual mineralogic occurrences.

Hussain (1987) developed a method of source-rock evaluation, similar to that developed by Meyer and Nederlof, for the characterization of source rocks in the state of Kuwait. Kristinik and Charpentier (1987) applied factor analysis to readings of gamma-ray, resistivity, sonic, density, and neutron logs of organic-rich rocks in the Bakken Formation. Using this technique, they defined the distribution of trends of variation in richness and maturity of those rocks for the whole Williston basin.

Source-rock evaluation using well logs has been developed during the last ten years and some controversy still exists in this area. While some studies show that the indication of organic carbon content defined from well logs is unreliable, others lead us to think that the responses of well logs are always consistent, reliable and in accordance with theoretical models. Some authors state that only the use of information from newer and more sophisticated tools
can lead to a reliable evaluation, especially in portions of rock sequences with limited source potential. Therefore, a better definition of how well logs can be efficiently used in the geochemical characterization of source rocks is needed.
APPROACH, DATABASE, AND METHODS

The basic suite of logs utilized in oil exploration in the Lagoa Feia Formation comprises gamma-ray, resistivity, sonic, density, and neutron logs. Achievement of advanced results studying these five curves, which are available in the vast majority of the wells studied, represents a great step in the understanding of the Lagoa Feia Formation and creates the possibility of generating new information using data already on file. In parallel, the use of newer and more expensive logging tools becoming available, in the definition of information not obtained or possible to infer from logs generated with the use of these standard tools, can be analyzed more comfortably.

The approach used in this study is based on the calibration of tool responses, using all the subsurface data available, and testing the consistency of methods developed. Useful techniques in the exploration of this rock unit can, therefore, be created, and the concepts can be applied in other areas using the same kind of approach.

In a previous study (Abrahão, 1987), almost 1,000 m of cores, from 54 wells, were analyzed to define the facies assemblages and the depositional history of the Lagoa Feia Formation. In the present work, the database generated by
that study is used, and more subsurface data are incorporated in order to achieve the final calibration of log responses.

The use of ES-LOG, a software package for log analysis, discussed below in more detail, was fundamentally important in all phases of this project.

**Database**

The database used in this study was provided by Petróleo Brasileiro S/A - PETROBRAS. Figure 3 summarizes the whole database and shows the basin location of the wells used in this study, highlighting the ones that were selected as key wells. The large amount of information released by PETROBRAS for this study is comprised of:

a) a log suite, for 137 wells, composed of gamma-ray, resistivity, and sonic logs. Density and neutron logs were available for most of these wells (125). These logs were available in the scales of 1:1,000 for all the wells and 1:200 for 41 that were chosen as key wells,

b) LIS-format tapes, for the key wells selected for the project (see Fig. 3), containing well-
Figure 3. Summary of the database available for this study, and location of the wells that penetrated the Lagoa Feia Formation. Full dots correspond to the key wells selected for this study. Well-log data for these 41 key wells were available in LIS-format tapes.
log data. Well-log data were requested in LIS-format tapes in order to be used in the ES-LOG,
c) data from more than 1,000 m of cores analyzed in a preceding study (Abrahão, 1987),
d) black and white, small-scale photographs of all cores in item c,
e) 47 thin sections covering mainly the reservoirs and the source rocks of the sequence,
f) samples of reservoir and source rocks from which 32 additional thin sections were cut at the Colorado School of Mines,
g) data on permeability, porosity, and chemical composition defined in the laboratory for 8 cores,
h) results of 44 drill stem tests (DST’s), usually representing tests performed immediately after the drilling of the intervals,
i) results of 20 wireline formation tests,
j) results of 166 production tests,
k) partial pressure histories and cumulative production of the oil fields that produce oil from the reservoirs within the Lagoa Feia Formation,
l) geochemical data from 102 wells (see below),
m) composite logs from 136 wells (see below).

Appendix V summarizes the database used in this study, listing all the wells used. Sequential numbers were used in substitution of well names. Wells chosen as key wells for this study are also indicated. In addition, for each well are listed its geographic coordinates, depths of the Lagoa Feia Formation, thickness of the formation, cores that had their data available for this study, and other data eventually available, such as: geochemical logs, measurements of TOC and vitrinite reflectance, results on well tests, thin sections from the cores, etc.

**Geochemical Logs**

Geochemical information was fundamental in this study for the calibration of well-log responses of the lacustrine shales. The geochemical logs available for 102 wells contained information gathered from:

a) 691 Rock-Eval pyrolysis results,
b) 1551 determinations of TOC on cuttings,
c) 65 determinations of TOC on cores,
d) 45 vitrinite reflectance measurements, and
e) 18 gas chromatography-mass spectrometry results from organic extracts.
An example of the geochemical logs available for this study is presented on Plate I, in pocket.

The geochemical analyses were performed on three different kinds of samples:

a) composite canned samples every 30 m, collected from cuttings every 3 m. This sampling procedure was used in the earlier stages of exploration in the basin, when the technique of definition of profiles of light gases was still in use for the definition of the top of the mature zones throughout the basin,

b) punctual non-composite samples collected in plastic bags, every 15 m, from cuttings, and

c) pieces of cores.

These geochemical samples were sent to the PETROBRAS research center where they were analyzed. Most of them were analyzed for TOC contents and some selected ones for Rock-Eval pyrolysis and generation of extracts. Extracts were analyzed through gas chromatography and in some cases gas chromatography associated with mass-spectrometry techniques (GC-MS). Most of the analysis results used in this study were from the composite samples collected every 30 m.

For the determination of TOC, only 5 g of the whole sample (can, bag, or core piece) are involved in the
analysis, while for the Rock-Eval pyrolysis only 200 mg of the sample are analyzed. These are very important aspects to bear in mind when comparing laboratory results with well-log evaluation of source rocks, as it will be discussed later in this work.

Composite Logs

The composite logs cited above are constructed on a combination of gamma-ray and induction logs (in some cases a sonic log is also plotted). On this combination log, the following information is added:

a) interpreted attitudes from dipmeter logs,
b) position and magnitudes of oil and gas shows,
c) summary description of cuttings,
d) interpreted lithology from the association of information from cuttings and core descriptions with well-log readings,
e) top and base of the main stratigraphic units,
f) paleontologic subdivisions, according to reports generated at the Petrobrás Research Center,
g) seismic values (2-way time) in levels where the vertical seismic profiles (VSP) are avail-
able,
h) engineering data, such as: casing sizes and depths, cement plugs, perforated intervals, etc.

**Methods**

As discussed previously, this study can be divided into two main parts. One covering the log responses in the reservoir rocks, and the other handling the source-rock characterization through well logs. Obviously, the methods that were used are different in these two parts. Some of the steps involved in the work were general and usually taken at the beginning or end of the work. Others were taken to cover specifics of reservoir and source rocks and are described separately after the general steps. In most cases, the steps covering specifics were taken in parallel in both parts.

**General Steps**

The general steps followed in this work are listed below:
1) Selection of the key wells for the study.

As discussed before, this study follows the one that covered the definition of paleoenvironments and depositional history of the Lagoa Feia Formation (Abrahão, 1987). The same number of wells was involved in both studies. Because of peculiarities of facies distribution within the alluvio-lacustrine sequence under study, the reservoir and source rocks were not encountered, or properly represented, in all wells. Therefore, the first step was the selection of the wells that had these two facies better represented.

2) Reformatting of data tapes.

Tapes that came from Brazil containing the well-log data of the key wells had the files organized through the backup facility of the VAX operational system, which is an incompatible format with ES-LOG. The program requires the use of tapes in LIS format, which is the plain format of raw data of log readings obtained in the field during well-log operations. Therefore, before starting the processing of the data, all formats had to be changed, in a somewhat complex and time-consuming operation.

3) Filtering of well-log data.

In LIS tapes, information on all curves are registered at each half foot (6 inches), even in cases where the
vertical resolution of the log is lower than that. The vertical resolution of well logs varies from one tool to the other. In order to normalize all the readings to the same vertical resolution, and, consequently, to avoid spurious results on the final presentations, all the log responses were filtered. On ES-LOG, equal, binomial, or user-provided weights can be used to filter the data on 3 to 201 data levels. Furthermore, pre-set weights, in number of 14, are provided by the software in order to smooth data in one log to a bed response similar to another. Using one of these pre-set weight functions, all curves were brought to the smallest vertical resolution of the deep induction curve (Fig. 4). This filtering procedure additionally helps to smooth out statistical variations commonly present in the nuclear logs, namely the density, gamma-ray, and neutron logs.

4) Study of thin sections.

Thin sections covering mainly the reservoir facies and shales in the sequence were analyzed. The main concerns in this thin-section study were: a) the characterization of important mineralogical constituents in terms of well-log responses, and b) the definition of pore structures and diagenetic features affecting the productivity of the reservoir rocks.
Figure 4. Filtered data of well-log readings using function available in the ES-LOG. Dotted lines represent the raw data of log readings and full lines the data after filtering to a vertical resolution compatible with the deep induction. Curve meanings, by their names, are presented in a glossary preceding references. Logs are from a well in the Badejo High area.
5) Study of consistency of the established models.

After models of evaluation for the reservoir and source rocks were established, the consistency of both was analyzed throughout the basin on the key wells utilizing the resources of ES-LOG.

**Evaluation of the Reservoir Rocks**

Relative to the reservoir rocks, after the main aspects with potential influence on log responses were derived from the study of cores, cuttings, and thin sections, the following steps were followed:

a) crossplotting techniques available in the ES-LOG were applied. These techniques involved mainly porosity crossplots and Pickett plots -- which will be discussed below -- where petrophysical parameters defined on the plots were correlated to observations from the core and thin-section descriptions and compared throughout the basin in oil-saturated (productive and non-productive) and water-saturated zones,

b) different models of evaluation available in the ES-LOG were tested in the reservoir rocks in
order to define the most suitable and more reliable, through comparisons with the behavior of these reservoirs when tested, in the large database of well-test results available, c) the approach to be undertaken in the evaluation of reservoirs in the sequence was derived, considering all the geological aspects affecting well-log readings observed in coquina reservoirs.

**Evaluation of the Source Rocks**

Regarding the source rocks, and again after the main aspects with potential influence on log responses were derived from the study of cores, cuttings, and thin sections, the following steps were followed:

a) a database, containing 163 intervals characterized by uniform and good-resolution log readings and presence of laboratory measurements for calibration, was built for statistical analysis,

b) crossplotting techniques were applied mainly through the use of the GRAPH facility installed in the VAX8600 at the Colorado School of Mines. The objectives were to understand the patterns
of variability of the data within the database, define applicable corrections and transformations to the data, and decide what kind of statistical techniques were potentially helpful in the generation of models of interpretation for the source rocks,

c) using STATPAC, also discussed below in more detail, the data, after corrections and transformations, were treated statistically mainly through discriminant analysis and multiple regression,

d) the results obtained from the statistical treatment of data were initially verified through crossplotting techniques where comparisons of results with laboratory data were performed,

e) using the facilities available in the ES-LOG those results could be implemented in the program. Through a combination of FORTRAN and PASCAL languages, the discriminant and regression equations, derived through the statistical treatment of the data, were introduced into the program in order to be applied in all the logged sequences for the
wells that had data available on LIS-format tapes,
f) through ES-LOG, values of TOC obtained by lab measurements could be introduced in the computer and easily correlated with the results of the application of the discriminant function and the regression equation,
g) the relationships among log responses, which characterize some of the geochemical parameters for the source rocks, were extended to other wells or intervals that did not have the geochemical parameters determined through analyses of cuttings.

The initial plan for the study of the source rocks in this research was to have all results calibrated to geochemical analysis performed on cores only. In this regard, new TOC measurements on cores were requested from PETROBRAS especially for this work, increasing the database by 65 measurements. The first overall analysis of the available database indicated that it would be more advantageous to calibrate the logs with analyses performed on cuttings because:

a) coring programs in the sequence were always designed to obtain samples of reservoir rocks
for petrophysical studies -- which, in fact, is the routine followed by most petroleum companies. Therefore, shales were sampled accidentally, were in small number in the database, and never representative of the best source rocks existing in the sequence,

b) because of the coring operations, and the consequent number of trips into the borehole, in parallel with changes in drilling parameters, borehole conditions in cored intervals are usually poor. Therefore, log readings in these intervals are commonly not reliable enough to be employed in the calibrations,

(c) a huge database of TOC measurements on cuttings was available and about 10% of them could be precisely correlated with good resolution and uniform log readings in reasonably thick intervals. Furthermore, the values of TOC for these measurements were in a much larger range than the range of values available from measurements on cores.

Therefore, a reliable and large enough database could be created for the statistical treatment of data, based on
geochemical measurements performed on cuttings.

Software Utilized

The opportunity to use software for log analysis and statistical treatment in this study increased the potential of achieving useful and applicable techniques, mainly because of the possibility of a quick test of the methods developed and a check of the overall results throughout the whole basin.

Several techniques and models existing in the ES-LOG were directly applied in the study of the reservoir rocks, and the facilities provided by this software were fundamental in the implementation of the results obtained through STATPAC in the statistical treatment of data for the source rocks.

ES-LOG

ES-LOG is a software package for log analysis developed by Energy Systems Technology, Inc. (Denver-Colorado) and recently installed in the VAX8600 at the Colorado School of Mines. All of the onscreen graphic facilities of the program can be used only through a single
Tektronix terminal existing on campus, installed in the Petroleum Engineering Department. Other terminals can be used but the graphic output will not be interactive and can only be seen after execution through a VERSATEC plotter. The program offers all the facilities necessary for complete well-log evaluation. Figure 5 shows the master and main introductory menus of ES-LOG for entering in the log analysis mode and all the options available in this mode. To satisfy the reader’s curiosity, this project was named UGLY as seen in the main menu in Figure 5 because lagoa feia in portuguese means ugly lagoon.

The graphic output available in ES-LOG was used to generate all the illustrations involving well-log data presented in this study. Therefore, a brief explanation of the features in these illustrations is necessary at this point. In the graphic output -- option G in the main menu -- two options were used.

In the first one, playbacks of log readings, or continuous curves generated through the use of the program, are presented. As an example, see the playback presented in Figure 4. For the presentation of results or data on playbacks, two scales are available: a) detail, 1:200, and b) correlation, 1:500. Data can be presented only on three tracks if the graphyic is to be seen in the screen of the
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**ENERGY SYSTEMS TECHNOLOGY - Denver, Colorado**

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### Return to Master Applications Menu

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**Figure 5.** Master and main menus of the ES-LOG. Entering on the log analysis mode, option A in the master menu, all the options presented in the main menu become available.
Tektronix terminal, and therefore interactively generated. Presentation of four tracks of information is available only through the VERSATEC plot, and it is not interactive. Each curve has a name that is presented between its code symbol over the track where the curve is shown. A maximum of five curves can be presented in each log track. A glossary, for the meanings of curve names appearing throughout this work, is presented at the end of this thesis preceding the references. The first digit of depth values presented in most of the illustrations of this study were purposely omitted.

The second form of graphic output used in this work was the crossplotting techniques available in the ES-LOG. On cross-plots, three options are available. The differences among them are related to the possibility of obtaining more information than that presented in two dimensions along the two axes, through the use of colors on the screen or on the color copier coupled with the Tektronix terminal. Figure 6 shows the menu available on ES-LOG for the execution of a Pickett plot. On option C in that menu, which appears not only for the execution of Pickett plots but for all kinds of crossplots in the program, the three options, above mentioned, are shown: a) X for a simple crossplot, b) Z for a Z-plot, and c) Q for a Quad-plot.
Figure 6. Menu for the execution of a Pickett plot using ES-LOG.
Crossplots just define the two-dimensional crossplotting of the data and show undistinguished clouds of points, each of which would represent a variable number of similar intervals. The number of points which occur at each cell is printed, rather than an anonymous symbol. This type of crossplot shows the relative densities of zones across the graph field and is known as a "frequency crossplot" (Doveton, 1986).

The Z-plot is a useful variant of the basic crossplot that allows a third variable (Z) to be added to the two variables which correspond to the two axes of the graph. For any zone, the variable chosen to be represented by this Z axes is translated into an integer scale. Crossplotting is done in the normal manner, but the symbol printed is the appropriate Z value. The resulting crossplot is a two-dimensional situation, but the plot acquires a tri-dimensional character in terms of the information given. On Z-plots obtained through ES-LOG, each point can be plotted through a number that represents a value along a scale in the bottom of the graphic. Just as an example, a Z-plot of a porosity cross-plot is shown on Plate II, where each point is plotted with a color and number that follows the scale of DRHO (well-quality indicator) on the bar presented on the bottom of the graphic.
On Quad-plots each point is plotted with a number that represents the amount of points plotted together in that cell in a color that follows the scale of a third variable. Therefore they add a fourth element of information that corresponds to the summation of the information given by frequency plots and Z-plots, but they can only be understood if colors are available. As an example, a Quad-plot of a Pickett plot is shown on Plate III, where in each cell the printed number represents the amount of points plotted together, in a color that follows the scale of gamma-ray presented in the bottom of the graph.

Additional options available for all of these crossplots that deserve further comments are:

a) the choice of a cutoff trace on option D, in the menu of crossplots (see Fig. 6). This cutoff trace will define if a point should be plotted or not based on its corresponding value in this cutoff trace. For example, in all plots presented in this thesis the cutoff trace selected was always DRHO -- corrections in the density log, which is a quality control curve -- and values in intervals with corrections above 0.11 g/cm$^3$ (usually indicative of bad hole conditions and consequently poor log
readings) were never plotted,

b) the choice of a discriminator trace in the same
option D, in the menu of crossplots (see Fig.
6). This discriminator trace will define zones
within the plot that are of particular interest
to be highlighted, and

c) the choice of a drop count on option E, again
in the menu of crossplots (see Fig. 6). In
this drop count a minimum number of counts in
each cell is selected. For example, when 1 is
used in the drop count, all points that are
alone in each cell are not plotted. This
selection is excellent to clean up spurious
values in the plots usually created by distinct
vertical resolution of different logs which in
some cases can conduct to misleading
interpretations.

Throughout this thesis, except for the plates in the
pocket, only black and white graphics will be presented and
then Z-plots were chosen. Therefore, all cross-plots
presented will have two axes, and the points will be plotted
using a number that follows the scale of the bar presented
in the bottom of the graphs, representing a third dimension
of information. Again, cutoffs of 0.11 g/cm³ in the DRHO
curve were used in all plots. Drop counts of 1 were also used, which implies that at least two points were encountered in each cell represented in all plots.

**STATPAC**

Multivariate statistical analysis was performed in this work to generate a model for the interpretation of geochemical characteristics of source rocks in the Lagoa Feia Formation. The RASS-STATPAC (VanTrump and Miesch, 1977) usually shortened to STATPAC was used in this phase. RASS is an acronym for Rock Analysis Storage System, whereas STATPAC stands for statistical package. The STATPAC was developed by the United States Geological Survey and consists of a series of microcomputer programs that are in public domain. The program was developed to be used in the statistical treatment of data in exploration geochemistry.

All of the multivariate and univariate statistical techniques can be applied using this program. Details on the techniques used in this work will be explained in the section in which the model for geochemical evaluation of source rocks is discussed.
GEOLOGY

Geological aspects involving the section under study were covered by previous works (Schaller, 1973; Castro and Azambuja, 1980; Bertani, 1984; Bertani and Carozzi, 1985a, 1985b; Abrahão, 1987), and they are applied and expanded in this study, especially those that can be recognized through well-log signatures. In this section, a summary of a preceeding study (Abrahão, 1987) is presented with emphasis on aspects that relate to the analysis of well logs.

The Lagoa Feia Formation in the Geologic Evolution of the Campos Basin

The pattern of north-northeast trending normal faults observed in the Campos basin reflects the extensional tectonics during the rifting episode that separated the African and South American continents. During that phase, structural highs produced by differential subsidence become prominent and separated the Campos basin from the Santos basin to the south (Cabo Frio arch) and from the Espírito Santo basin to the north (Vitória arch). These basement highs are transverse to the coast and concordant with the
projections of main transform faults on the Atlantic sea floor (LePichon and Hayes, 1971; Bertani, 1984).

In the Campos basin, all the sedimentary sequence deposited during this rifting phase, in addition to a final evaporite cover, constitutes the stratigraphic sequence of the Lagoa Feia Formation. The fault system that developed during the rifting period created an irregular system of sub-basins with a mosaic of horsts and grabens in which syntectonic alluvio-lacustrine sediments were deposited. Basic volcanioclastic rocks are commonly interbedded with the Lagoa Feia Formation, especially at its basal portion.

The first marine incursions that invaded the system of sub-basins formed during the rifting period were associated with conditions of tectonic quiescence. A topographic barrier to the south provided the low clastic influx and the restriction necessary for extensive deposition of evaporites that occur in the top of the Lagoa Feia Formation.

After the rifting period, the only tectonic activity in the Campos basin was subsidence and basinward tilting along faults largely inherited from the rifting process. The sedimentary overburden, associated with tilting, generated salt tectonics resulting in growth faults and minor salt domes. Salt tectonics generated highs and lows along the Campos basin affecting the distribution of facies of the
units deposited after the Lagoa Feia Formation.

The continuous process of drifting between Africa and South America generated pure oceanic conditions in the basin. In this stage of evolution, sediments formed in a carbonate platform, laterally associated with fluviodeltaic sandstones and shales deposited near the border of the basin, represented by the Macaé Formation (see Fig. 2).

As the basin tilted to the east, because of differential thermal subsidence, a regressive sequence of shaly clastics was unconformably deposited over the Macaé Formation. Continuous tilting and subsidence, associated with sea-level changes, controlled open-marine clastic sedimentation on the basin, from the Upper Cretaceous to the Recent, which is represented by the Campos and Embore Formations (see Fig. 2).

Facies Assemblages

Three main facies assemblages, representing three main depositional environments are recognized in the Lagoa Feia Formation:

a) volcaniclastic conglomerates and sandstones deposited on alluvial fans along basaltic escarpments generated by rift tectonics,
b) oxidized shales and sandstones, and secondarily carbonates, deposited on mud flats between the alluvial fans and lake shorelines, and
c) lake deposits from near to offshore, mainly represented by the unique reservoirs of coquina and lacustrine shales, which are organic-rich in some levels.

Figure 7 shows two schematic stratigraphic cross-sections along perpendicular directions in the Campos basin, where the lateral relationships through time among these three depositional environments is depicted. In the figure, well positions are shown with the environmental interpretation of their sections; environments between wells are inferred.

Alluvial Fans

Volcaniclastic conglomerates and sandstones, originated on proximal to distal portions of alluvial-fan complexes, present in some cases pelecypod shells in their framework showing that some of the basaltic escarpments were very close to the lakes. Towards the northern part of the basin, the volcaniclastic content of the conglomerates, although still significant in volume, appears to decrease. Probably
Figure 7. Schematic stratigraphic cross-sections along two perpendicular directions in the Campos basin.
in this region of the basin, the volcanic activity was less significant during the rifting period causing the exposure of older, non-basaltic rocks to denude some of the escarpments.

As can be seen in Figure 7, conglomerates are more common in the basal portion of the Lagoa Feia Formation and become frequent again close to the top of this rock unit, before the deposition of the evaporite cover. In the middle portion of the sequence, conglomerates are usually absent or represented by thin layers, which indicate that alluvial fans were geographically important at the beginning and at the end of the evolution of the Lagoa Feia Formation, reflecting stronger tectonic activities in these periods of the rifting phase.

Because of the geometry of the lake basins, elongated along and bordered by north-northwest trending normal faults, alluvial fans entering the lakes and forming fan deltas are commonly recognized in the sequence.

Mud Flats

In general, siltstones, sandstones, and shales, some of them with desiccation cracks and growth of evaporites, and carbonates represented by areas of algal mats or even
development of stromatolite heads, are the more commonly observed facies forming in these flats. They are here called mud flats due to the predominance of fine-grained siliciclastic deposits. All of these rocks formed between the lake margins and the alluvial fans, almost always close to lake shorelines.

As can be seen on Figure 7, and probably because of the geometry of the lake basins, with abrupt escarpments along their major axes, facies change within short distances from alluvial fans to deep lake waters. Therefore, mud flat deposits are not expected to be volumetrically important between the escarpments and the lakes. This fact may explain the relative dearth of these deposits compared to the predominance of alluvial fans and lake sediments in the Lagoa Feia Formation.

Lake Deposits

Lacustrine sediments in the Lagoa Feia Formation include basically two kinds of deposits:

a) green to gray, in some cases black and organic-rich, shales deposited in deeper portions of the lakes, and
b) carbonates composed of shell beds which form coquina deposits that, when pure and porous,
constitute the main reservoir rocks within the sequence. They exhibit different proportions of shell fragments and siliciclastic or carbonate matrix. They are dominated by pelecypod valves and ostracodes, but in some levels gastropods occur.

Figure 8 shows, in a block diagram, the schematic distribution of facies during Lagoa Feia deposition, representing most of the geologic conditions implied for this formation, and how these facies accumulated through time. As can be seen in the diagram, facies relationships are strongly controlled by the distribution of normal faults along the basin and consequently by the geographic distribution of grabens and horsts.

**Age of Deposition**

The marginal Brazilian basins, such as the Campos basin, developed during the later separation of South America from Africa, starting at about 140 Ma (Emery et al., 1975). At this stage of development, small basins and troughs began to take shape and received continental sediments that eventually became very thick. At that time
Figure 8. Schematic distribution of facies during most of the time of deposition of the Lagoa Feia Formation (from Abrahão, 1987).
the African basins were contiguous with those in Brazil. The basin system was separated when the continents drifted apart, some segments remaining with South America and some with Africa. Dating of this separation is necessarily inexact, as it consists of a series of overlapping events, as follows:

1) thinning of the continental crust,
2) initial extension that produce narrow and deep grabens,
3) volcanism and dike emplacement, and
4) deposition of continental sediments followed by marine sediments.

The separation is not simultaneous because these different tectonic phases happen at different times along the new margin.

Along the Brazilian coast, continental separation began in the Late Jurassic in some regions and in the Early Cretaceous in other areas. The separation between the two continents began at the south and proceeded northward, occupying a time span of approximately 50 million years (Burke, 1975).

In Brazil, due to a very rich ostracode fauna, it was possible to obtain an accurate biostratigraphic zonation for the continental sediments accumulated during the rifting
period. The zonation of such sediments, based on the abundance of these ostracodes within the continental deposits of coastal Brazilian basins, led to the establishment of six local stages: Don João (Late Jurassic), Rio da Serra, Aratu, Buracica, Jiquiá, and Alagoas, roughly corresponding to the international stages distributed from the Neocomian to the Aptian (Vianna et al., 1971).

In the Campos basin, within sediments of the Lower Cretaceous belonging to the Lagoa Feia Formation, only the upper stages of Alagoas, Jiquiá, Buracica, and Aratu are encountered, whereas in other marginal basins such as the Recôncavo/Tucano and Sergipe/Alagoas older stages are present.

Although some of the local stages defined in these Brazilian basins have a problematic correlation with the international stages, a tentative correlation is presented in Figure 9. The correlation presented is drawn from Moura (1985) and from personal communication with the SECASU group at PETROBRAS, whereas the absolute ages for stage boundaries are gathered from Haq et al. (1987).
Figure 9. Chronostratigraphic subdivisions used in this study for the sediments of the Lagoa Feia Formation compared to other Brazilian basins and to international age boundaries (combined and modified from Moura, 1985, and Abrahão, 1987).
Summary of the Geologic Evolution

A major tectonic pulse related to the initiation of the rifting between Africa and South America occurred at some time close to the end of the Jurassic. This pulse resulted in uplift and block faulting of the basement, which formed a graben system (Figure 10, time 1). As the grabens continued to subside, basement block faults formed sub-basins (Figure 10, time 2). Subsequent erosion of the high blocks filled these sub-basins with alluvial-fan deposits and lake sediments. Volcanic activity associated with the sedimentation during the Aratu and Buracica stages was very significant.

During the initial phase of the Jiquiá stage, sequences of nonmarine carbonates, shales, sandstones, and conglomerates formed the depositional pattern (Figure 10, time 3). At times, intralake highs were submerged, and probably when the lakes were deeper, anoxic conditions developed within them. Sporadic basement faulting resulted in discontinuities formed within the lake sequences deposited during the Jiquiá stage. This period represents the time when the lake deposits were at their maxima (Figure 10, time 4).

This depositional cycle ended by a pulse of basement
Figure 10. Schematic stages of evolution of the Lagoa Feia Formation. Time 1 = Rio da Serra (?), time 2 = Aratu/Buracica, time 3 = Early Jiquiá, time 4 = Late Jiquiá, time 5 = Alagoas, time 6 = end of Alagoas (from Abrahão, 1987, modified from Brice et al., 1982).
faulting generating uplift and a regional unconformity. After this tectonic event, arid conditions prevented the deposition of large lacustrine sequences during the Alagoas stage (Figure 10, time 5).

Subsidence continued through the Alagoas stage culminating with the region being invaded by marine waters from the south/southeast. Evaporites were deposited under tectonically quiescent conditions (Figure 10, time 6), and probably extended farther eastward than the older sedimentary sequence. In fact, they may have covered part of the originally shallow oceanic crust, that was already being created in the central portion of the rift system. The sub-basins were filled with evaporites which grade upward, and in some areas laterally, into a dolomitic unit mainly in the central and southern portion of the basin. The final stage shown in the diagram on Figure 10 represents a possible stratigraphic cross section of the basin at the end of the deposition of the Lagoa Feia Formation. The diagram is slightly modified from one presented in a study developed for the Cabinda basin in the west African coast (Brice et al., 1982).
Similarities with the Recent Lake Basins of East Africa

Through the application of uniformitarianism, the recent lakes of the East African rift system can be used to better interpret the Lagoa Feia Formation. Overall, the similarities between these recent lakes and the stratigraphic record of the Lagoa Feia Formation are:

a) the tectonic setting in which the east African lakes developed is the same in kind, magnitude and processes as the one that occurred during the Mesozoic separation of Africa from South America,

b) the spatial distribution of significant geologic features seems to be similar to the one so far recognized within the geologic record of the Lagoa Feia Formation,

c) sedimentary facies, especially their distribution, are generally comparable between these two areas, and being so, the sedimentary processes involved in the deposition can be compared,

d) climatic variations, as interpreted in the sedimentary record, are recognized in both sequences, and
e) the chemistry of lake waters today in Africa, and their variations through time, seems to correlate to what can be deduced for the Lagoa Feia paleolakes.

Other features, including drainage systems and historical evolution, can be compared and seem to be remarkably similar in most cases.

Analogs from east Africa are very useful, especially those involving sedimentary processes in operation in the rifting environment and the paleochemistry of the lakes, although two main differences exist between these two systems:

a) siliciclastics are much more abundant in the sedimentary sequence of the Lagoa Feia Formation than it would be supposed from the observations of siliciclastic deposition in east Africa today, and

b) extremely arid conditions, as the ones observed in the east branch of the rift in Africa (with deposition of thick beds of evaporites in Lakes Magadi and Natron, for example), apparently did not occur during the evolution of the Lagoa Feia Formation. Only sparsely distributed levels of carbonate with evaporitic habit have
been identified and should represent the most severely arid conditions in the Lagoa Feia sequence.

In the sequence of the Lagoa Feia Formation a mixing of characteristics is observed, especially among those observed today on lakes in the western branch of the East African rift system.
WELL-LOG INTERPRETATION

As discussed in the last section, the Lagoa Feia Formation is characterized as an alluvio-lacustrine sequence deposited under an active tectonic regime during a rifting period. Unique features, linked to this kind of evolution and these depositional environments, make well-log interpretation in this sequence a very difficult task, because of the association of two main factors.

The first factor is related to unusual mineralogic occurrences. Lake sediments usually develop on closed basins and show higher sensitivity to climate changes. In the Lagoa Feia Formation there is evidence that the chemistry of the lake waters was very different from normal sea water, and that common and substantial fluctuations in salinity and water chemistry occurred (Abrahão, 1987). In consequence, minerals or mineral assemblages (some of them unusual) with potential influence on log readings occur in this sequence, such as:

a) stevensite, \((\text{Mg}_{2.44}\text{Al}_{0.07}\text{Fe}^{3+}_{0.03})\text{Si}_{4.13}\text{O}_{10}(\text{OH})_2\) (Tettenhorst and Moore, 1978), in some cases associated with talc, and occurring almost always as oolites, which are very common in the basal portion of the sequence, in the portion
where the influence of volcanic activity is stronger,
b) pyrite, which is very commonly associated with the sequence deposited in periods when lake sedimentation occurred in anoxic bottom conditions,
c) organic carbon, which is related to the same periods of anoxia in these lake bottoms, deposited in some levels in relatively large amounts, accumulated mainly on fine-grained, siliciclastic rocks, and usually associated with overall mineralogical changes in these rocks,
d) zeolites, which are very common as cements in the sequence; zeolites are the result of the diagenetic alteration of volcanoclastics that are associated with the whole sequence, although more frequent in the basal portion,
e) phosphate nodules, which are frequently observed in shales,
f) silica cements, which are common in reservoir facies as well as silica replacement in several carbonates, forming nodules in some cases,
g) dolomite, which, although rare, is present as
replacement of calcite.

The second factor is associated with abrupt, and in some cases very frequent, variations in facies along the sequence. Because of the evolution in closed basins, and again the consequent higher sensitivity to climate changes in association with the active tectonic regime, abrupt vertical and lateral facies changes are common within the sequence. Lateral discontinuities make correlation difficult, and vertical discontinuities can cause variations in mineralogical contents that require complete changes of models for well-log interpretation in small intervals of depth. In some cases these changes occur at a frequency that the vertical resolution of most logs is unable to detect.

Models for well-log interpretation were developed mainly for systems where silica, calcite, and dolomite are present. These models can handle the presence of evaporites or shales, but in this instance well-log interpretations become much more complex. As stated by Moss and Harrison (1986), reliable results may be obtained from three or four log measurements provided that the formation under study is a simple mixture of quartz, dolomite, and limestone, and that the analyst is content to parcel the non-matrix material into a "composite" mineral called "shale".
An additional problem in the well-log evaluation of the Lagoa Feia Formation is represented by the unusual pore structure existing in the reservoirs of coquina. The coquinas are pure shell beds that present unique pore distributions of shelter, moldic, and vuggy interconnected porosities. On the other hand, models developed for the evaluation of hydrocarbon contents of reservoir rocks assume that those rocks have intergranular porosities, or that they closely behave as reservoirs with intergranular porosities (Archie, 1942; Rasmus, 1987).

Therefore, in the Lagoa Feia Formation well-log interpretation is complex and only the statistical calibration of the logs with characteristics observed on cores or cuttings can lead to a better resolution for the evaluation models. With this procedure, important features of the reservoirs and the source rocks are evaluated in the models.

As shown in a previous study (Abrahão, 1987), the overall characteristics of the lake basins that generated the Lagoa Feia Formation changed through time, leading to different characteristics for the stratigraphic sequence during its evolution. On Figure 11, a composite stratigraphic column for the Lagoa Feia Formation shows the most common and important features observed in most of the
Figure 11. Composite stratigraphic column of the Lagoa Feia Formation. I = upper portion, II = middle portion, III = lower portion (modified from Abrahão, 1987).
wells utilized in this study. Although innumerable heterogeneities are observed along the section, the unit can be divided roughly into three logically different portions that present similar characteristics (see Fig. 11). Peculiarities in the section affecting well-log responses in each one of these three portions are discussed below, in more detail.

The Lower Portion

The lower portion of the Lagoa Feia Formation is characterized by deposition during intense tectonic activity, and by the existence of smaller lake basins representing the initial stages of the lacustrine system. The thickness of the sediments that accumulated during this period is relatively small and dominated by volcaniclastic conglomerates and siliciclastics derived from them. Fossils are not common and coquina reservoirs are minor. Due to smaller areas occupied by the lakes, and maybe their intermitent character, dark, organic-rich shales also are not common. The sediments in this part of the sequence commonly show high dips (see dipmeter log on Figure 11) indicating higher tectonic instability during
deposition, or significant structural modification in the section after deposition.

Oolites of stevensite are frequently identified in this portion of the sequence (Fig. 12). Stevensite is a mineral of the smectite family, very rich in magnesium. The presence of this mineral indicates high magnesium contents in the lake waters during its deposition, which is due to the intense volcanic activity close to the lakes where the flocculation of this mineral occurred. This mineral presents high crystallinities indicating that chemical precipitation in oolites (Fig. 13) was its principal formation mechanism (Carvalho et al., 1984). Associations with talc are common.

The presence of stevensite oolites along this portion of the sequence strongly affects well-log readings (Fig. 14). Resistivities are very low as well as densities. Neutron porosities and transit times are very high. Usually the borehole walls are deeply caved. These characteristics were earlier attributed to high pore pressures existing in the section (Pereira, 1980) but, in fact, they are more likely related to the higher water content associated with the stevensites. Being from the smectite family, stevensites are clays that can hold more water (up to a factor of ten) than the nonexpandable clays, such as illites, kaolinites, and chlorites (Chilingar, Fertl, and
Figure 12. Oolites of stevensite observed in the lower portion of the Lagoa Feia Formation. Sample is from 4360 m, well # 36, in the central portion of the basin.
Figure 13. Photomicrograph (crossed nicols) of stevensite oolites within the lower portion of the Lagoa Feia Formation showing the common habit of this mineral in concentric layers within oolites. Slight deformation occur in the oolites, which are ellipsoidal due to compaction effects. Thin section cut from the same sample presented on Figure 12.
Figure 14. Common log responses in the lower portion of the Lagoa Feia Formation where stevensites are abundant. Low gamma-ray readings in this section, where shales and siltstones are abundant, are explained by the low K⁺ content in the lake waters from which stevensites precipitated. Well log is from a well located in the Badejo High area.
Yen, 1985). Although oolites of stevensite are usually deformed (see Fig. 13), compaction effects in this portion of the section were not transmitted completely to the accumulations of this mineral. Therefore, the common evolution observed for the smectites, with continuous expulsion of water at increasing depths, and the consequent transformation to illites, it is not observed for the stevensites in this section. Effects on well-log readings in this portion of the section are similar to those observed in shallower sections that are rich in smectites: swelling clays, poor borehole conditions, and anomalously high porosities and low resistivities.

However, the most distinctive characteristic of this section on log responses is the low overall gamma-ray values. Higher gamma-ray readings would be expected, because it is a predominantly low energy depositional environment, and most of the rocks of this section can be described as shales, mudstones, or siltstones. These low gamma-ray readings are explained by the chemistry of lake waters necessary for the precipitation of stevensite. According to Carvalho et al. (1984), precipitation of stevensite requires low concentrations of $K^+$, $Ca^{2+}$, and $Fe^{2+}$ relative to $Mg^{2+}$. Because of these necessary low concentrations of $K^+$, which is one of the elements
responsible for the net gamma-ray responses, it is understandable why low gamma-ray responses characterize the section where stevensites are abundant in the shales of the Lagoa Feia Formation.

Occurrences of stevensite are not unique to the lacustrine sequence of the Lagoa Feia Formation. The same mineral, presenting in some areas the same habit of occurrence, is described in the Eocene lacustrine Green River Formation in the state of Utah (Bradley and Fahey, 1962; Tettenhorst and Moore, 1978) (Fig. 15). The stevensites in the Lagoa Feia Formation are light to dark brown in color (Fig. 16), probably because of the encompassing of organic matter among the oolitic layers during the precipitation of this mineral, in the same fashion that it is described in the Green River Formation. Significant amounts of TOC (2%) were reported by Tettenhorst and Moore (1978), who suggested an algal origin for the organic matter, from algae known to occur in the lake where the Green River Formation was deposited.

Although levels of organic matter can be high in some horizons within this section, the results of this work, applied to the characterization of source rocks in well logs in the Lagoa Feia Formation, are not valid for this lower portion. The effects of stevensites could not be properly
Figure 15. Photomicrograph (crossed nicols) of oolites of stevensite described in the Eocene Green River Formation. Surface rock sample collected close to the city of Ephraim in Utah (acknowledgments to Dr. Ken Stanley, currently with Exxon Co., USA, for the release of the sample).
Figure 16. Photomicrograph (plain light) of stevensite oolite in the Lagoa Feia Formation. The brown color is probably caused by accumulation of organic matter, as described in the oolites of stevensite in the Green River Formation. The oolite in the photo is the same one presented in the northeast corner of Figure 13.
evaluated because of commonly bad hole conditions (see Fig. 14) and scarcity of geochemical analyses in the database for the calibration of the small amount of satisfactory log readings obtained in this portion of the section.

The Middle Portion

The middle portion of the Lagoa Feia Formation (see Fig. 11), which constitutes the main objective of this study, represents the period when the lake basins were at their maxima in this area of the Brazilian coast. In this portion, lake deposits are thicker and widespread. Layers of pure shells, deposited mainly close to lake shorelines, form the unconventional reservoirs of coquina, which are the only producers so far recognized in the Lagoa Feia Formation. These rocks are interbedded with shales, deposited in deeper portions of the lakes. During periods of stratified columns of water in these lakes, the bottoms were anoxic, and organic-rich shales accumulated, forming the source rocks responsible for all the oil discovered to date in the Campos basin.

Overall, the sedimentation rates during this period were faster than in other periods. The dips within this
section are low (see Fig. 11), compared to the ones that occur in the lower portion, showing that the tectonic activity significantly decreased.

This is the main portion of the Lagoa Feia Formation in terms of oil exploration. Results of this study are valid for this portion of the section. Well-log responses and models of evaluation for these rocks are discussed in detail in the next sections.

The Upper Portion

The upper portion of the Lagoa Feia Formation (see Fig. 11) was deposited after a last tectonic pulse that generated a regional unconformity. Over this unconformity surface, sediments were accumulated at low rates of deposition, probably under arid conditions. Lake sediments during this period are practically absent. Volcaniclastic conglomerates and sandstones dominate the sedimentary pattern (Fig. 17). They represent a long-lasting period of denudation followed by subsidence, or lowered base level, or both. In consequence, conditions for the entrance of the sea to the basin were created, an event that generated the evaporitic cover over the entire sequence of the Lagoa Feia Formation.

Figure 18 shows the common log responses in the upper
Figure 17. Volcaniclastic conglomerate as commonly observed in the upper portion of the Lagoa Feia Formation. Sample is from 2143 m, well #66, in the western portion of the basin.
Figure 18. Common well-log responses in the upper portion of the Lagoa Feia Formation. Gamma-ray values are high, compared to expected responses in clean reservoirs, and the neutron/density separation is indicative of high shaliness. These responses are not always related to clay content, but to the mineralogical content of the rock fragments that are the main constituent of these rocks. Well log is from a well located in the western portion of the basin.
portion, which usually present a monotonous response of intermediate values of gamma-rays, as well as neutron and density porosities. Resistivities are predominantly low except in levels where the calcareous content of the rock (usually caliche levels) increases. The evaporite cover is almost always represented by anhydrite with comparable thickness throughout the whole basin. Halites are much less frequent. However, when halites are present the thickness of the evaporites increases considerably, from averages of about 60 m to 300 m or more. In restricted areas of the basin, dolomites are present where halites and anhydrites are absent, indicating some lateral facies variations in the evaporite cover. Thin layers of shales, interbedded with these evaporites, may present potential source-rock, but they could not be characterized through well-log responses because of the small database for calibration.

The conglomeratic section is commonly discarded in the evaluation for the presence of hydrocarbons, because the well-log responses are attributed to an assumed high clay content for these rocks. Care should be exercised in this well-log evaluation, because in fact, high clay contents are not always present. The gamma-ray responses and separations observed between the values registered in the neutron and density logs, which are typical indication of clays in the
conventional approach to well-log evaluation, are in reality connected to log responses of the minerals that appear in the fragments of volcanic rocks, which are the most frequent constituent of the conglomerates. Nevertheless, the chance of producing good reservoirs is always small because of the diagenetic alteration of these volcaniclastics into zeolites, which usually clogs up the porosities existing in these rocks (Fig. 19).

These aspects, related to reservoir quality for the conglomerates in this portion of the sequence, are valid for all the coarser siliciclastic rocks present in the entire Lagoa Feia Formation. The overall characteristics of these rocks are relatively constant throughout the sequence. As discussed before, towards the northern part of the basin the volcaniclastic content of these siliciclastic rocks decreases and then chances for potential permeable reservoirs are higher (Abrahão, 1987).
Figure 19. Photomicrograph of a volcanioclastic reservoir showing rock fragments and almost no porosity, mostly because of filling by alteration of volcanics into zeolite minerals. Thin section cut from core at 3304 m, well # 66, in the western portion of the basin.
RESERVOIR ROCKS

As discussed in the previous section, the reservoir rocks that produce oil in the Lagoa Feia Formation are mainly distributed over the middle portion of the sequence. They are coquinas, represented by shell beds of primarily pelecypods. Several diagenetic stages affected these rocks (Carvalho et al., 1984) and transformed these coquinas into very heterogeneous zones. In some cases, profound variations in reservoir quality occur over relatively short vertical intervals. On the other hand, reservoir-quality rocks occur (Fig.20), reaching net-pays of up to 20 m of almost continuously porous and permeable rock (Abrahão, 1987). In these reservoirs, porosities are seldom very high. Common values are about 12%, with a maximum of about 20%. However, hydrocarbons are produced from porosities as low as 4 to 6% because of usually good permeabilities related to interconnected vuggy porosities.

Although porosity types in the Lagoa Feia Formation can be classified as shelter, vuggy, and moldic following the classification of Choquette and Pray (1970), they will be always referred as vuggy in this study, following the approach of Lucia (1983) in which vuggy porosities include those three types. According to that author, vuggy
Figure 20. Coquina reservoir. The rock is brown in color because of oil staining. Pelecypod shells are the only constituent fragments in this rock. Sample is from 2719 m, well # 129, in the Badejo High area.
porosity is defined as the pore space larger than or within the particles of rock and commonly presented as leached particles, fractures, and large irregular cavities. Lucia (1983) concluded that the petrophysical and productive characteristics of the rocks that present vuggy porosities is related to the type of vug interconnections. He classified vuggy porosities, according to the type of interconnections among them, in: a) separate vugs, which are connected through the interparticle pore space and defined by percent porosity, and b) touching vugs, which are connected to each other and defined by absence or presence.

Figure 21 shows the porosity-permeability relationships existing in the coquinas. Particle sizes in these rocks are typically around 3 to 5 mm. In some cases, pore sizes are larger than particle sizes, and this fact may explain why even low porosities may generate high permeabilities. In most cases, small porosity increments increase permeability considerably. Following the classification of Lucia (1983), part of the vugs in the coquinas are touching vugs, and they appear to create good permeability conditions for these rocks.

Coquina deposits are probably associated with wetter periods in well-developed lake basins when, because of the higher amount of fresher water in the system, the lakes
Figure 21. Porosity-permeability relationships existing in the coquinas of the Lagoa Feia Formation.
expanded, became interconnected, and life flourished. Individual shell blankets of up to 40 km long and 5 km wide along some coastal segments of Lake Tanganyika, in the East African rift system, were recognized by Cohen (1987) who interpreted them as a result from a combination of mud-winnowing processes related to periodic changes in lake level or current activity and subsequent biological reworking.

Although occurring in a section where overall rates of sedimentation were faster compared to other portions of the Lagoa Feia Formation, good coquina reservoirs were apparently formed under conditions of slow rates of deposition on the borders of the lakes, where wave action was intense, and the shells had the chance to be completely winnowed and early cemented (Fig. 22). Early cementation appears to be a key for the preservation of porosity in these reservoirs. This early cementation protected the shells from later diagenetic effects, mainly pressure-solution. Rocks deposited in areas where wave action was less intense were poorly winnowed, not early cemented, and later affected by pressure-solution generating extremely low-porosity non-reservoir rocks (Fig. 22). In parallel, and as noticed by Bertani (1984), accumulations of ostracode-rich coquinas are related to periods of
Figure 22 (next page). Early cementation effects on coquinas. On (A) (2719 m, well # 129, Badejo High area), the unusual but typical pore structure of these reservoirs is illustrated. On (B) (2120 m, well # 58, south from the Badejo High area), poorly winnowed, low-porosity coquina is shown. Both thin sections are stained with alizarin Red-S, showing that calcite is the mineral forming the shell fragments.
hypersalinitities, shrinking lakes, and probably reduced wave action generating poorly winnowed rocks that never constitute good reservoirs along the sequence (Fig. 23).

Cementation in these coquinas is described mainly as sparry calcite, occasionally replaced by silica in a later diagenetic stage (Carvalho et al., 1984). However, early cementation by silica may also have occurred, because layers indicating several generations of silica cement are present in some intervals (Fig. 24).

In alkaline lakes, like the ones where these sediments were formed, there is a high possibility of early cementation by silica, because silica solubilities are enhanced in high-pH environments. Drever (1982) reported that the chemistry of waters associated with ultramafic rocks, because of the reactivity of the minerals involved, usually have very high values of TDS. In these waters, magnesium is systematically preponderant, an pH values can be very high, between 11.0 and 12.0 in most cases. High pH’s result because the dissolution of Mg-silicates consumes H+, driving the pH up. Degens (1965) pointed out that in the case of some feldspars, amphiboles, and clay minerals the pH at the solid-liquid interface of minerals, resulting from hydrolysis, may be as high as 9.0 to 11.0.

Eugster and Jones (1979) studying the brines of Lake
Figure 23. Ostracode-rich coquina showing poor reservoir characteristics. Sample is from 2690 m, well # 13, in the western portion of the basin.
Figure 24 (next page). Neomorphized pelecypod grains cemented by several generations of silica cements on crossed nicols (A) and plain light (B). This is a closer view of the same sample presented on the top of Figure 22; 2719 m, well # 129, in the Badejo High area.
Magadi, in the East African rift system, concluded that silica is lost from solution in the lake waters through the formation of opaline cements and crusts. They reported the pH in Lake Magadi between 9.0 and 10.0 and under these circumstances the solubility of amorphous silica increases rapidly (Fig. 25). Although silica is known to dissolve readily in alkaline solutions, its solubility increases sharply only when the pH raises above 9.0 because of the ionization of $\text{H}_4\text{SiO}_4$. Therefore, in alkaline solutions up to a pH of about 9.0, silica is no more soluble than in strong acids (Degens, 1965). Eugster and Jones (1979) studied brines generated in other closed basins around the world and observed that the final silica enrichment in certain lakes is not as pronounced as in others, because the necessary pH levels are not reached in some of the most concentrated brines. The association with ultramafic or mafic rocks in the source area of these closed basins appears to be a key factor in the generation of high-pH waters in the lakes.

Silica cements are common, therefore, in the coquinas of the Lagoa Feia Formation because of the high alkalinity of the waters at Lagoa Feia time. Because of the close association with volcanics, conditions for solution of silica were created in the high-pH waters, and consequently
Figure 25. Effects of pH on the solubility of silica (compiled by Degens, 1965).
high silica contents were common in the percolating near-surface fluids. These early silica cements are not only observed in the Lagoa Feia Formation and in Lake Magadi, but also in the Green River Formation (Scholle, 1978), probably because of the involvement of similar geochemical conditions.

Well-Log Responses of Coquinas

In terms of well-log responses, typical coquina reservoirs (Fig. 26) are usually characterized by:

a) extremely low gamma-ray readings, indicating very "clean" rocks,

b) commonly low porosities derived from the readings in the density and neutron logs. These porosities are even lower when calculated from the readings in the sonic log,

c) high to very high resistivities, characteristically heterogeneously distributed along the whole coquina interval being water or oil, or both, the fluids present,

d) good developments in the spontaneous potential curve, indicative of unusually good
Figure 26. Common well-log responses of coquina reservoirs. This reservoir of coquina presents an oil/water contact at x810 m. Variability in resistivity values is high, even within the water zone. Log is from a well located in the Badejo High area.
permeabilities.

Additional examples of well-log responses of coquinas are presented in the Appendix I.

Slight increases in gamma-ray responses are connected to zones not completely winnowed and usually indicate poor permeability conditions in the reservoirs. These slight increases in gamma-ray, that commonly imply much poorer reservoir conditions, are interpreted as "shaliness" in these reservoirs but, in fact, they are not properly related to clays alone, but to a mixing of clays and micrite.

Because of the presence of heterogeneities, higher resistivities, predominant dual mineralic composition (calcite + silica), and unusual pore structure (see Fig. 22), well-log evaluation of these unconventional reservoirs is usually problematic. They cannot be interpreted as pure carbonates, as they were in the early stages of exploration in this formation, because the silica cements have to be considered in the responses in all logs.

When the coquinas are considered pure carbonates, the Archie equation, with saturation and cementation exponents used for "average" limestones applied to porosity values derived from the density logs, commonly produces optimistic results. Several intervals evaluated by this simplified Archie equation produced only water in zones of calculated
low water saturations (between 30% and 50%). Therefore, only the comparison of results of hydrocarbon production in well tests with water saturations defined through well logs in the coquinas, taking into account the peculiar characteristics of these reservoirs, will define the minima of water saturations in which water-free production of hydrocarbons can be expected. Adjustments in the methods of calculation of these water saturations, especially in low-porosity intervals, have to be developed based on the same comparison and on mathematical models developed for the behavior of vuggy-porosity rocks.

**Definition of Parameters for the Evaluation**

The procedures for the evaluation of the potential for oil production of reservoir rocks through well logs involve a series of steps where several aspects are studied separately. In these steps, the main parameters that will be necessary for the evaluation are defined.

The fundamental parameters for the evaluation through Archie, or any other method derived as a more sophisticated or modern approach in relation to Archie, will always involve the definition of the lithology of the reservoir
rock, porosity (\(\Phi\)), resistivity of the formation water (\(R_w\)), true resistivity of the rock (\(R_t\)), cementation exponent (\(m\)), and saturation exponent (\(n\)).

**Lithology**

Lithology is one of the most important "parameters" to be defined in the process of evaluation of a reservoir rock. Models of evaluation will be different, and the amounts of porosity can vary significantly, because the kind of lithologies that constitute the reservoir rock is the fundamental parameter entered in the equations that transform log readings into porosity values.

Porosity crossplots (Fertl, 1981) are powerful evaluation tools involving the readings of two different porosity logs and commonly used for simultaneous definition of porosity and rock matrix (Fig. 27). These crossplots add a degree of definition that is lacking in the basic porosity determinations made from single well logs. However, the kinds of minerals "mixed" in the rock are almost never known exactly, because there is always a measure of ambiguity concerning the precise mineralogical composition of many zones. A mixture that is most likely is always assumed from other information, usually from cores or cuttings. The cause of the ambiguity is the relationship between the
Figure 27. Neutron-density porosity crossplot. The position of the clouds of points of an interval define the kind of matrix (lithology), with indications of mixings of different matrices, and define more appropriate porosity values than when porosity is defined from a single log measurement (modified from Schlumberger, 1985).
number of "knowns" which are supplied (the porosity logs), and the number of "unknowns" to be resolved (porosity plus mineral components). Two logs can be analytically solved in terms of three unknowns (since the unknowns collectively constitute a closed system). If pore volume is an unknown, a unique solution in terms of only two minerals can be made. Therefore, three minerals may only be independently evaluated if all three porosity logs (sonic, neutron, and density) are considered simultaneously (Doveton, 1986). The neutron-density is the most advantageous porosity crossplot to be used, because shale effects are less confusing in this plot, due to the opposite influence of clays on the readings of the density and the neutron logs. Crossplots are quite helpful in resolving almost all the major lithofacies, but even these crossplots fail to identify the amount and composition of minor constituents (Rahman and Jacka, 1986).

Core and thin-section descriptions and definition of mineralogy in laboratory confirm a dual-mineral system when the coquinas are clean and porous, which is represented mainly by the calcareous shells with calcite and silica cements. Therefore, one crossplot of porosities probably should produce reliable results in terms of porosity values and the amount of mixing between silica and limestone.

Neutron-density porosity crossplots were used in the
characterization of lithology in the coquinas. In fact, the log readings in these reservoirs clearly define the mixing between limestone and silica for the rock matrix, especially in high-porosity intervals (Fig. 28). On low-porosity coquinas, the indication of mixing is not so clear (Fig. 29). This fact is related to the lower probability of percolation by silica-rich solutions in these lower-porosity intervals, and the consequent lower probability of early cementation by silica.

**Porosity (Ø)**

Porosity determination in coquina reservoirs is difficult, because models of interpretation of log responses were developed assuming intergranular porosities. First of all, it is fundamental to understand that porosity determination from well logs is always a matter of interpretation, because in all kinds of logs grouped as "porosity logs" this parameter is not measured directly, but it is estimated by interpretation of a measurement affected by porosity (Porter, Pickett, and Whitman, 1969).

Because the coquinas are a dual-mineral system, the erroneous value of density or transit time of the matrix, when considering them as pure limestones, can lead to
Figure 28. Neutron-density porosity crossplot for high-porosity coquina. The oblique line represents pure limestones in the crossplot. The cloud of points is in between limestones and sandstones, showing the mixing of these two matrices, as evidenced on cores and thin sections. Interval is from a well located in the Badejo High area.
Figure 29. Neutron-density porosity crossplot for low-porosity coquina. The cloud of points is closer to the line of limestones, although some indications of less pronounced mixings with silica are present, especially in "cleaner" rocks (lower gamma-ray values). Interval from a well located in the central portion of the basin.
optimistic values of porosity of about 2%. This increase can be significant in these reservoirs, because it may be about 50% of the total porosity of the rock in low porosity intervals, which are common.

Furthermore, the definition of porosity in the coquinas involves another very important aspect, which is related to the definition of what is called "secondary" porosity. "Secondary" porosity is jargon used in log analysis, that is confusing with the concept of secondary porosity in geology. The geological concept of secondary porosity refers to the development of porosity after the deposition or emplacement of the rock, through processes such as solution or fracturing (Bates and Jackson, 1984). In log analysis, the "secondary" porosity corresponds to the difference in porosities registered by the sonic log in relation to the porosities usually defined through the readings in the density log. "Secondary" porosity defined through well logs is measured in terms of secondary porosity index (SPI), which is represented by:

$$SPI = \frac{\varphi_e - \varphi_s}{\varphi_e}$$

where: $\varphi_e = \text{effective porosity of the rock (fraction), determined from the combination neutron/}$
density, and

\[ \phi_s = \text{porosity (fraction)} \text{ detected by the sonic log, based on acoustic transit time of the matrix defined through the neutron/density method.} \]

"Secondary" porosity, as defined through well logs in the approach described above, can be interpreted as the fraction of non-intergranular porosity of the rock, because the sonic log reads the transit time of sonic waves through the reservoir, and these waves tend to travel faster through continuous rock material. Consequently, it does not detect the amount of porosity due to vugs, molds, and sub-vertical fractures.

The well logs in the coquinas of the Lagoa Feia Formation usually detect relatively high indices of "secondary" porosity (Fig. 30), what confirms the unusual pore distribution in these rocks observed in the study of thin sections (see Fig. 22). In the well log evaluation of oil-producing coquina reservoirs it was very common to observe reasonably high SPI's. Therefore, interconnection of vuggy porosities, creating touching vugs, is a very important factor improving the permeability of these reservoirs. This may be the main aspect that transforms these reservoirs into good oil producers, even at average-
Figure 30. "Secondary" porosities as indicated by log readings in coquina reservoirs. Sonic porosities are lower in almost all coquinas (low gamma-rays) on this interval. The lower porosities defined through the sonic log leads to calculations of SPI's usually between 0.25 and 0.35, being the values higher towards lower porosities. Same well interval as the one presented on Figure 26.
low porosities, similarly to what is explained by Hirakawa and Myiake (1983) in the development of a general method for the interpretation of carbonate reservoirs.

**Resistivity of Formation Water (Rw)**

The definition of values of resistivity of formation waters were reasonably problematic in the beginning of the exploration in the coquina reservoirs of the Lagoa Feia Formation. Today, because of the large database available, these values are not so confusing, and good relationships have been established, in this study, for resistivity of formation water versus depth throughout the Campos basin.

The function of Rw values versus depth was derived for the range of depths in which these coquinas occur in the Campos basin (Fig. 31). The function is based on values of resistivity of waters from drill stem and production tests that recovered large volumes of formation waters -- because of their lower chances of being contaminated -- and on the bottomhole temperatures extrapolated from values of maximum temperatures registered during well-log operations.
Figure 31. Definition of Rw values for the coquina reservoirs throughout the Campos basin. In (a) the values of salinities measured in samples from well tests that recovered larger volumes of formation waters are plotted (dots), showing a steady increase with depth. Values of salinity from tests with smaller recoveries (triangles) and salinities defined through well logs, Rw minimum method (crosses), are also plotted. In (b) extrapolated temperatures from well log operations are shown; another steady increase with depth. In (c) the relationship between Rw and depths, derived using chart Gen-9 (Schlumberger, 1985), is shown.
True Resistivity of the Rock (Rt)

True resistivities of formations are defined as the resistivity of the fluid-filled rock where the fluid distributions and saturations are representative of those uninvanced, undisturbed part of the rock (SPWLA, 1984).

Resistivity logs can be roughly divided into two main kinds: a) those that measure conductivities and transform the measurements in resistivity values, and b) those that measure resistivity directly. The choice of the most adequate kind of resistivity log to be used depends on the relationships among the resistivities of muds used in the boreholes, resistivities of formation waters, and magnitudes of porosities in the formations of interest (Schlumberger, 1987).

The relationships among resistivity values, on measurements performed at different depths of investigation in a borehole, permit the definition of the true resistivity of formations through the use of diagrams known as "tornado" charts. In the coquinas of the Lagoa Feia Formation, due to very high resistivities and commonly low porosities, the most appropriate resistivity log to be used is the laterolog, which belongs to the kind that measures resistivities directly. Induction logs (conductivity
measurers) can present errors in their readings, especially towards high-resistivity intervals. Unfortunately, in the early stages of exploration in the Lagoa Feia, the well log more commonly used was the induction, and therefore, the vast majority of resistivity logs available in the database were registered through induction tools. Laterologs started to be used in the coquinas just recently. Therefore, uncertainties may exist in the "true" resistivities (Rt) used for the coquinas in this study, especially towards high-resistivity intervals.

**Cementation Exponent (m)**

The exponent m, described initially in the Archie equation (Archie, 1942) as the "cementation exponent" or "cementation factor" is now widely accepted as a measurement of the tortuosity of the pore geometry to current flow (Rasmus, 1987). In fact, m is regulated by the tortuosity of the pore network, but this is the complement of the matrix geometry, which is in turn controlled by the rock texture. The "cementation factor" is therefore a loosely generic term that reflects the composite effect of a host of textural properties (Doveton, 1986). According to Rasmus (1987) this approach to the physical meaning of the exponent m only applies to the tortuosity of intergranular
porosities, although it is commonly extrapolated to other pore geometries. Water-filled fractures and vugs both represent less tortuous paths, yet fractures appear to decrease the cementation exponent dramatically while vugs appear to increase them. Unconsolidated sands were found to have m's of about 1.3, whereas highly cemented rocks had m's of about 2.2 (Rasmus, 1987).

Lucia (1983) studied the relationships of m values and the different kinds of vuggy porosities that he established and concluded that m values on carbonates with vuggy porosities are related to the ratio of separate vugs to the total porosity, a ratio that he called the vug porosity ratio. This relationship is shown on Figure 32 where the approximate equivalent relationship established for the coquinas in the Lagoa Feia Formation is added. As shown on Figure 32, m values increase with the increase in the vug porosity ratio.

Pickett plots (Pickett, 1966; 1973) are another powerful aid for well-log interpretation because they can solve evaluation problems in intervals where key parameters for the evaluation, such as Rw and m, are not known. These plots can also give indications of presence of fractures or vug porosities in the reservoirs (Fig. 33). They work very well in the coquina reservoirs of the Lagoa Feia Formation.
Figure 32. Measured values of m versus vug porosity ratios. The same relationship is valid for the coquinas of the Lagoa Feia Formation, which values, represented by the hatched box, were added to the figure (modified from Lucia, 1983).
Figure 33. Overall characteristics of a Pickett plot. The position of the points will define the orientation of the straight lines in the interval under study. From the orientation and position of these straight lines, rock parameters are derived (modified from Asquith and Gibson, 1982).
and show systematically high values of $m$ (Fig. 34). In fact, these rocks can be considered as highly cemented, and because of the existence of separate vugs creating vug porosity ratios up to 40%, high values for cementation exponents are really to be expected. Values between 2.15 and 2.5 were observed on Pickett plots of coquina reservoirs.

**Saturation Exponent**

The exponent $n$, described initially in the Archie formula (Archie, 1942) as the saturation exponent, might bear certain similarities to the cementation exponent $m$, but not necessarily the same value (Ransom, 1984). The saturation exponent is related to the influence of insulating fluids on the shape and continuity of the electrically conductive solutions occupying pore volumes (SPWLA, 1984). Therefore, oil wettabilities affect the measured saturation exponent. There has been little published literature reporting measured saturation exponents in vuggy or fractured rocks.

According to Rasmus (1987), artificially consolidated sands containing water and air (believed to be water-wet) exhibit a saturation exponent of 1.82 while the same
Figure 34. Pickett plot of coquina reservoirs. The slope of the straight line (Sw=100%) defines high values of m for the coquinas. Interval from a well located in the Badejo High area.
material with water and oil mixtures (believed to be oil-wet) have saturation exponents of 2.51. Rasmus (1987) showed that rocks with vuggy porosities present a total water saturation lower than it would be expected for a given resistivity index. The net result is that the saturation exponent is lower than 2.0 in a situation where the cementation exponent is greater than 2.0, because it is a vuggy-porosity rock. Rasmus (1987) did not appreciate the aspects involving separate and touching vugs in his considerations, but apparently developed his concepts over vuggy-porosity rocks where separated vugs predominated. Nevertheless, it is clear in his work that in vuggy-porosity rocks different values for m and n are to be expected.

On the other hand, and according to the physical meaning accepted for the exponent n, Ransom (1974) showed that this exponent increases when oil saturation is above critical, and insular globules of oil become interconnected throughout the porous rock framework. This fact causes n to keep increasing until the water volume has been reduced to irreducible films.

Basically, values of 2.0 have been systematically used in the reservoirs of coquina, but a more coherent approach can be developed taking into account the pore structure of these reservoirs, as will be discussed below.
Evaluation Approach

The main factors complicating the evaluation of coquinas are related to the pore structure of these reservoirs and to the commonly low porosity existing in these rocks. Models developed for reservoir evaluation have shown to work on intergranular porosities. Mathematical modeling to explain the behavior of vuggy-porosity reservoirs is just starting, and therefore many more laboratory measurements of rock parameters will be necessary before efficient models can be attained. Furthermore, there is an apparently drastic change in the behavior of the coquinas of the Lagoa Feia Formation when porosity is reduced to small fractions, implying that models of evaluation for these reservoirs have to compensate for these variations in low-porosity intervals. Possibility of changes in the wettability of the coquinas, becoming oil-wet towards lower porosities, could explain extremely high resistivities in several of these low-porosity intervals.

Therefore, the evaluation of the precise amount of oil existing in these coquinas is still a hard task and can be just approximated when the appropriate parameters are entered on traditional methods of reservoir evaluation.

As stated above, poor results have been obtained in the
evaluation of coquina reservoirs using the simplified approach to the Archie equation without the compensation for the behavior at lower porosities. In addition, porosity values have been commonly derived from the density logs using limestone matrix, which is commonly in error in intervals where silica cements are present.

Elliott (1983) showed that the use of saturations below 50% as an indicator of oil production is a pitfall in log analysis. This is clearly the case of the coquina reservoirs. According to Elliott (1983), several factors are important in the absolute magnitude of connate water in a reservoir rock including, for example:

a) the history of the oil accumulation in the originally water-saturated rock,
b) the viscosity of the oil,
c) the interfacial tension between oil and water,
d) the grain size distribution of the rock,
e) the proximity to the oil-water interface (capillary pressure effects),
f) the clay content of the rock, and
g) the detailed geometry of the pore space.

In individual producing formations, the amount of connate water (as % of the pore space) must be at the irreducible minimum to have water-free hydrocarbon
production. This irreducible minimum for water-free production varies from about 2% to about 70% in the producing formations throughout the western world (Elliott, 1983).

There is a common tendency to assume that water saturation values below 50% are indicative of oil-producing zones. This happens because the relative permeability of oil in presence of water usually increases considerably above oil saturations of 50%, for the average reservoir-fluid system conditions. But this observation is not true for all cases. Again, depending upon the same factors related by Elliott (1983), the water percentage at which the relative permeability of oil increases can vary considerably as well as the minimum at which water-free hydrocarbons are produced.

Using ES-LOG, all coquinas were studied through Pickett plots. Productive intervals of coquinas showed very low water saturations (Fig. 35), even when varying values of m and n towards high values were used, which represent more cemented and less porous rocks. Therefore, comparing the results of well-log evaluation with the behavior of the coquinas in terms of oil production, this hydrocarbon-rock system shows peculiar characteristics where the water-free hydrocarbon production occurs only at lower water
Figure 35. Pickett plot of oil-producing coquinas. Water saturations are usually very low, always below 30%. Interval from a well located in the Badejo High area.
saturations (roughly about 30%).

Models available in ES-LOG for evaluation of oil reservoirs were tested to select the best model for evaluating coquina reservoirs in the Lagoa Feia Formation. The model that worked best used the "Shell formula" for characterization of water saturations (Schlumberger, 1985). The Shell formula gives increasing values of m at lower porositites, and it is more in accordance with the vuggy porosities that occur in these rocks (Fig. 36). Furthermore, high values of n have to be expected in low-porosity coquinas, because the pore structure of these reservoirs will create increasing insulation for the continuity of electrically conductive fluids at these lower porosities. These two approaches adopted for the values of m and n entered into the Archie equation with porosity values derived taking into account mixings of silica with carbonates lead to more realistic values for water saturation in the coquina reservoirs, especially towards the low-porosity zones.

Another important aspect to bear in mind in the evaluation of coquina reservoirs is related to the concept of bulk volume of water (BVW). The BVW is the product of a formation's water saturation and its porosity, thus:
Figure 36. Resistivity formation factor versus porosity. This chart shows the relationships of $F$ vs. $\phi$ commonly used in well-log interpretation. Highlighted is the relationship defined by increasing values of $m$ at lower porosities, which was used in this study in the evaluation of the coquina reservoirs (modified from Schlumberger, 1985).
BVW = Sw × Ø

If values of BVW are constant or close to constant within a reservoir, they indicate that the zone has its pore-size homogeneously distributed and that it is at the irreducible water saturation, or in another words, it will produce water-free hydrocarbons. The irreducible water is water that will not move, because it is held on grains by capillary pressure (Asquith and Gibson, 1982), or electrical forces. Because the amount of water a formation can hold by capillary pressure increases with decreasing grain sizes, the bulk volume of water also tends to increase with decreasing grain size.

In the coquinas, bulk volumes of water are extremely low in oil-producing zones. Small increases in bulk volume of water are always associated with the production of water in well tests. Figure 37 shows that, compared to other reservoirs, the behavior of coquinas approximate the ones with the lowest bulk volumes of water (values between 0.005 and 0.01). This happens because porosity is usually low, but the pores are big, and then only small amounts of water will occur as films of water electrically bounded to pore walls, or occupying very small pores where oil cannot enter due to capillary forces. Therefore, irreducible water
Figure 37. Behavior of coquinas in irreducible-water zones (a) compared to the behavior of other reservoirs (b). BVW's in oil-producing coquinas are extremely low, usually between 0.005 and 0.01 ((a) is from an interval of a well located in the Badejo High area; (b) is from Asquith and Gibson, 1982).
saturations are very low, resulting in calculations of extremely low bulk volumes of water (BVW) in oil producing reservoirs.

Using ES-LOG, the approach derived in this study for the evaluation of the coquina reservoirs was applied in all coquinas in the key wells and compared to results of fluids produced in well tests. This comparison led to the establishment of the following characteristics, typical of oil-producing coquinas in the sequence:

a) water saturations are almost always below 30%. Some intervals with saturations between 30% and 50% produced only water when tested,
b) bulk volumes of water are extremely low and constant, showing relatively homogeneous distribution of pore sizes and very low irreducible water saturations,
c) higher values for cementation and saturation exponents lead to more realistic values of water saturations in low-porosity intervals.

Figure 38 shows a comparison of saturations calculated by Archie and the ones calculated by the approach used in this study. Plate IV, in pocket, shows a colored example of these results from another well. Additional examples of evaluation of coquinas performed in this study are presented
Figure 38. Final evaluation obtained for the coquina reservoirs. Values calculated by Archie are lower in all intervals compared to the saturations obtained in this study. Extremely low values of BVW occur in oil-producing intervals, which are always zones with Sw < 30%. Interval from a well located in the Badejo High area.
and commented in the Appendix II.

Table I shows a sequence of procedures to be followed in the evaluation of the coquina reservoirs according to the approaches developed in this study.

<table>
<thead>
<tr>
<th>STEP</th>
<th>DESCRIPTION</th>
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<tbody>
<tr>
<td>1</td>
<td>Definition of Lithology. - Using the density-neutron porosity crossplot, the amounts of limestone and silica in the rock matrix are defined.</td>
</tr>
<tr>
<td>2</td>
<td>Definition of Porosity. - The density-neutron porosity crossplot may be used in the definition of porosity values. If the readings of the density log are used to derive porosity, a value of matrix density between limestone and silica has to be used, following the definition of lithology on step 1.</td>
</tr>
<tr>
<td>3</td>
<td>Definition of m. - Using Pickett plots, values of m are defined.</td>
</tr>
</tbody>
</table>
Definition of n.- Values of n are usually high in the coquinas. M=n seems to be the best approximation to be adopted.

Definition of Rw.- Using charts presented on Figure 31, Rw values are defined.

Calculation of Sw.- Entering the parameters defined above, Sw's are defined using the common Archie formula.

Calculation of BVW.- Values of BVW are calculated using the expression:

\[ BVW = \phi_e \times Sw \]

Definition of potential pay zones.- Zones with saturations below 30%, presenting very low and continuous values of BVW have high potential for producing water-free hydrocarbons.

The method of well-log evaluation presented in this study for the coquinas was developed just by grouping all the observations on the database and by studying in detail the well-log responses of these reservoirs. Relatively few key wells were oil producers in the coquinas, because they are very similar in terms of well-log responses and occur only in the Badejo High area. Therefore, the small database of well-log measurements was not suitable for the
application of statistical techniques, and in consequence, confidence intervals cannot be provided for the average numbers furnished in this part of the study.

Results obtained from the application of this method of evaluation may suffer from the following limitations inherent to its development:

a) the behavior of vuggy porosities is not yet completely understood. The use of high m and n exponents in the Archie equation, as shown in this study, was a good approximation for obtaining more reliable values of $Sw$. Nevertheless, models for the evaluation of coquina reservoirs will have to be adjusted to new mathematical models of vuggy-porosity behavior, when developed.

b) in areas where the coquinas cannot be characterized as dual-mineralic systems, as defined in this study, a different approach may be required for their evaluation. Occurrence of different kinds of cement in these rocks (zeolites for example) or different diagenetic products (strong dolomitization for instance), if present in not-yet-drilled areas in the Campos basin will have also to be calibrated to
their correspondent log readings.
c) the definition of better numbers of minima for
water saturations and maxima of bulk volumes of
water in water-free producing coquina
reservoirs will be possible with the
application of statistical techniques on
results obtained in the evaluation of coquinas
using the approach derived in this study. A
larger database of log readings, including
areas where new oil occurrences are discovered,
will be the main factor creating conditions for
the application of these statistical
techniques.
SOURCE ROCKS

Shales that occur above the stevensite-rich lower section of the Lagoa Feia Formation were deposited in the offshore portions of the lake basins existing during the rifting period. Phosphate nodules are observed in some levels (Fig. 39), and in periods when stratified columns of water existed in these lakes, dark, organic-rich layers were formed under anoxic conditions (Fig. 40). In some levels the richness in organic carbon is very high, and values of up to 14% TOC (total organic carbon), or organic carbon content in weight percent, were observed.

In thin sections, variations in the amounts of organic contents in different laminae are always observed associated with mineralogic changes in the rock. Usually the organic-rich levels are characterized by decreasing clay contents. Pyrite is also observed in these organic-rich layers and recognized in thin sections under reflected light (Fig. 41).

Earlier studies in the Campos basin have shown that the organic-rich shales belonging to the Lagoa Feia Formation are apparently the only source rocks mature enough for the generation of hydrocarbons in the entire stratigraphic section of the basin (Pereira, 1982; Meister, 1984; Figueiredo et al., 1985; Pereira, Trindade, and Gaglianone,
Figure 39. Typical shale of the Lagoa Feia Formation. This green, laminated shale presenting phosphate nodules is from 2688 m, well # 87, in the area of the Badejo High oil fields.
Figure 40. Black, organic-rich shale, is shown in the base of this piece of core, which is from 4530 m, well # 43, in the central portion of the basin.
Figure 41 (next page). Photomicrographs of a organic-rich shale, showing variations in mineralogical content and richness in organic carbon, in different laminae (A). Not all of the dark material is organic carbon. Under reflected light (B) pyrite is identified among the layers. Thin section was cut from a piece of core at 4973 m, on well # 37, in the central portion of the basin.
1985). None of these studies, however, have characterized how rich these rocks are, or the variations in their richness within the basin. These are important factors to be related to the distribution of these rocks within the sequence, and geographically within the basin, needed to generate a database for volumetric calculations of hydrocarbon prospects.

The importance of source rocks to petroleum exploration was very efficiently illustrated by Murris (1984) who, after examining a number of worldwide basins, reported that the drilling success ratio dramatically improved when geochemical parameters were employed in the evaluation of hydrocarbon prospects. A productive source rock is a necessary condition for a productive formation, and yet source rock identification and evaluation is largely ignored by traditional wireline formation evaluation (Herron, 1987). These considerations make clear that the delineation and characterization of potential source rocks by wireline logs vastly enhance petroleum exploration and basin analysis.

Waples (1985) presented a method for the definition of hydrocarbon generation involving three basic parameters, which must be addressed in the evaluation of source rocks:

a) the quantification of the organic matter, TOC,
b) the identification of the type of organic
matter, defined by Rock-Eval pyrolysis and best represented by the hydrogen index (HI), and c) the determination of the maturity level of the organic matter.

Still, according to Waples (1985), a basic equation can be used to calculate hydrocarbon volumes generated from source rocks, which is represented by:

\[
\text{Volume of HC} = (k) (\text{TOC}) (\text{HI}) (f)
\]

where TOC is expressed in weight percent, hydrogen index (HI) is given in mg HC/g TOC, and maturity is represented by a fraction (f) between 0 (completely immature) and 1 (fully mature). The value of the conversion constant (k) is governed by the units desired for the hydrocarbon volumes and by the assumptions about the density of the source rocks and hydrocarbons. The equation defines hydrocarbon generation per cubic mile of source rocks. Obviously not all hydrocarbon generated will be expelled by the source rock, and threshold values for each sequence have to be considered in this approach.

With this simple but very effective approach, if reliable TOC indication can be obtained in a continuous or near-continuous basis, quantitative analysis of prospective areas will be much improved. Consequently, the well-log
definition of TOC contents, a parameter of paramount importance in quantitative basin analysis, should always be sought by well-log analysts in all basins.

Herron (1987), when introducing a new tool for source-rock evaluation, suggested that the use of the standard suite of well logs leads to poor results for source rocks below 2.0 to 3.0 percent in weight of organic matter. Furthermore, she regarded as disadvantageous the necessity of a correlation for calibration of well-log data with cores on a well-by-well or regional basis, in order to get reliable indications of TOC from well logs. In spite of Herron’s objections, other authors have tried to establish relationships among log measurements (of individual or combined log readings) and TOC measured in laboratory using the standard suite of well logs. These studies appropriately show that, when the correct geological and operational constraints in each case are taken into account, and the databases furnish statistically significant amounts of data, the results are usually very good (Meissner, 1978; Schmoker, 1979, 1981; Schmoker and Hester, 1983; Dellenbach, Espitalie, and Lebreton, 1983; Hester and Schmoker, 1987; Kristinik and Charpentier, 1987).
Well-Log Responses of Organic Carbon

The presence of organic material in potential source rocks, significantly affects geophysical wireline responses (Fertl, Chilingarian, and Yen, 1986), because:

a) Kerogen, depending on its composition, has an average density close to 1.0 g/cm³ (Mendelson and Tokuş, 1985), in a range that rarely exceeds the interval between 0.9 and 1.1 g/cm³,

b) travel times of sonic waves are increased by kerogen, and average values of 180 usec/ft are reported (Mendelson and Tokuş, 1985), although depending on the composition and nature of the organic matter, the range of variation can be between 150 and 185 μsec/ft (Fertl, Chilingar, and Yen, 1986),

c) hydrogen indices of organic matter are near 0.67, i.e., 2/3 as many hydrogen atoms as the same volume of water (Mendelson and Tokuş, 1985),

d) as organic carbon is electrically non-conductive, high TOC contents can increase the resistivity of the host rock above the resistivity value of the same rock devoided of
e) geochemically, the association of organic carbon with uranium is well known. The oxidation of the quadrivalent uranium occurs very easily in early phases of weathering and the ion $U^{4+}$, which is insoluble, forms the complex $UO_2^{2+}$, called uranyl, where uranium is in the form of $U^{6+}$ which is very soluble and, therefore, very mobile. Under reducing conditions, the ion $UO_2^{2+}$ forms numerous complexes with organic compounds (Goldschmidt, 1954), and that is one of the reasons why uranium shows strong correlation with organic matter.

Therefore, although uncertainties related to the physical and chemical properties of organic matter are commonly present, rocks with high amounts of organic carbon are expected to show overall low bulk densities and attenuate sonic waves, showing higher transit times. On the other hand, organic carbon replaces mineral matter, and because of its higher hydrogen contents, will increase the readings in the neutron logs (neutron response is related to the overall hydrogen content of the rock), and may also affect the readings in the resistivity logs. Furthermore,
because of the geochemical association with uranium, high gamma-ray readings are also expected.

In fact, according to Mendelson and Toksöz (1985), bulk density is very sensitive to TOC. An increase of 10% TOC (by weight) causes decreases of almost 0.5 g/cm³ in the overall bulk density of the source rock. The vertical resolution of the density sonde is approximately 2 ft (60 cm). At shale densities of 2.25 g/cm³ or greater, the minimum concentrations of organic matter for the density log to respond to is about 1% (Meyer and Nederlof, 1984). On the other hand, bulk density readings may not be reliable indicators of organic matter due to varying pyrite concentrations (density about 5.0 g/cm³). Geochemically, organic matter, because of deposition in anoxic conditions, is often directly related to pyrite contents. Furthermore, density logs are more affected by rugosity of the borehole walls than other porosity logs and, together with varying amounts of pyrite, may furnish misleading indications of amounts of organic carbon in some stratigraphic sequences.

Unlike the effects on density logs, high TOC contents can always increase the apparent $\Delta t$ value, although the effect of kerogen on travel time can be dependent on the shape of the inclusion, and the distribution mode within a given formation, e.g., dispersed versus laminated
(Mendelson and Toksöz, 1985; Fertl, Chilingar, and Yen, 1986). If the organic matter is in the form of plates, it can have a stronger effect on velocity than implied by equations governing the log responses on mixings of different substances. As noticed by Meyer and Nederlof (1984), source rocks containing the so-called kerogenous organic matter, which is derived from aquatic organisms and bacteria, are usually laminate, whereas the humic organic matter, which is derived from land plants, is usually dispersed through the sediments, with the exception of coal. Although various mixtures of these different types of organic matter may occur, different responses on sonic logs can be observed in rocks with the same amounts, but different kinds of organic matter.

Regarding resistivity logs, most authors have agreed that the effects of organic carbon are detected only on mature source rocks. In fact, the effect of organic matter on resistivities is more related to the existence of oil in the source-rock interstices when it is mature, than on increasing resistivities caused by immature organic matter. The measurements on resistivity logs are more related to the fluids existing within rock interstices. Because electrically non-conductive organic matter replaces mineral matter, it may not create a significant contrast when
immature within a rock with comparable electrical properties in its matrix.

Gamma-ray responses in source rocks are commonly anomalous, because these rocks generally exhibit high concentrations of uranium. In addition, the thermal diagenesis of the organic matter does not affect the uranium concentrations. Uranium remains with the residual organic matter because it does not follow the hydrocarbons generated by the cracking of kerogen (Meyer and Nederlof, 1984). Although most source rocks exhibit high gamma-ray responses associated with high concentrations of uranium (Mendelson and Toksöz, 1985; Autric and Dumesnil, 1985), some low-gamma-ray responses in source rocks have also been recognized (Schmoker and Hester, 1983; Meyer and Nederlof, 1984; Fertl, Chilingar, and Yen, 1986). This aspect of gamma-ray responses in source rocks is discussed below in more detail.

Sediments can be regarded as consisting of heavy and light fractions. The heavy fraction is the mineral matter, and the light fraction is the formation fluids. In source rocks, the contained organic matter, because of the physical properties of kerogen, is also part of the light fraction. Therefore, different kinds of logs will be affected differently, depending on the contrast of the properties
between the fraction that affect the log measurement and kerogen. Furthermore, during compaction, water is expelled. Because of the presence of organic matter, source rocks retain a greater amount of the light fraction than lean sediments, and then can appear on some logs to be somewhat less compacted (Meyer and Nederlof, 1984). Compaction effects can also create more pronounced effects on log readings of source rocks.

**Database of Log Responses**

When compared to normal shale sequences, the log readings on shales existing in the Lagoa Feia Formation show a series of anomalies (Fig. 42), chiefly represented by:

a) some readings on porosity logs show higher values than expected from the normal trends of compaction of these rocks,

b) resistivity increases are common; in some cases extremely high resistivities are observed,

c) gamma-ray values are commonly very variable. Although rare, peaks of very high values occur,

d) separations observed between the curves in the
Figure 42. Well-log responses of shales. Anomalous porosity values occur at x230, x245, x258, and x270 m. At about x270 m, gamma-ray is unusually high. Resistivity increases in some of these levels. Shales below x300 m show completely different log characteristics. Well log is from a well located in the southern portion of the basin.
density and neutron logs are also not homogeneous, and
e) borehole walls are commonly in unusually good condition in some shale intervals.

Additional examples of log responses of shales of the Lagoa Feia Formation are presented in the Appendix III.

In this study, 163 "samples" of log responses were selected in these shales, corresponding to zones sufficiently thick for high quality log readings to be correlated with laboratory measurements. The 163 sets of log readings were divided into groups based on the correspondent values of TOC measured in laboratory for each set. Three groups were chosen based in the following correlations:

a) lean rocks, correlated with TOC values below 0.5%,
b) marginal rocks, correlated with TOC values between 0.5% and 2.0%, and
c) source rocks, correlated with TOC values above 2.0%.

This subdivision follows the approach derived by Waples (1985), in which rocks containing less than 0.5% of TOC are considered to have negligible hydrocarbon-source potential, rocks containing TOC between 0.5% and 1.0% are considered
marginal, and rocks containing more than 1% TOC often have substantial source potential, although only TOC values above 2.0% are indicative of highly reducing environments with excellent source potential.

Furthermore, according to Waples (1985), the amount of hydrocarbons generated in rocks with less than 0.5% TOC is so small that expulsion simply cannot occur. The kerogen in such lean rocks is almost always highly oxidized and thus of low source potential. On the other hand, rocks with TOC between 0.5% and 1.0% will not function as highly effective source rocks, but they may expel small quantities of hydrocarbons and thus should not be discounted completely. Kerogens in rocks containing less than 1.0% TOC are generally oxidized, and thus of limited source potential. Still, according to Waples (1985), some rocks with TOC values between 1.0% and 2.0% are associated with depositional environments intermediate between oxidizing and reducing, where preservation of lipid-rich organic matter with source potential for oil can occur. According to Jones (1980), the majority of the world's major oil accumulations originated in source rocks with a total of organic carbon content in excess of 2.5% by weight.

Therefore, the approach followed in this study for the grouping of log readings corresponds to a summation of both
approaches discussed above (Jones, 1980; Waples, 1985). Rocks with TOC’s between 1.0% and 2.0% were considered marginal, because Waples (1985) points out that only 2.0% TOC is a sure indicative of good source rocks, and Jones (1980) establishes that only rocks with TOC above 2.0% have effectively generated larger amounts of hydrocarbons. This approach was also adopted taking into account the statistical treatment of the data performed in this study, which is discussed below.

Porosity Logs

"Porosity" values on shales are much more a response to water content than the effective porosity of potential reservoir lithologies. The burial of muddy sediment and its progressive compaction in subsidence by loading of later sediments is a well-known phenomenon. The degree of compaction is matched by decreasing transit time, increasing densities, and decreasing neutron porosity readings. The basic trend corresponds to a nonlinear function of depths, with rapid changes at shallow depths which curve exponentially downward toward an asymptotic value (Doveton, 1986).

The raw values on density, sonic, and neutron logs in
the Lagoa Feia shales were converted into porosity values to deal with a similar magnitude of values. For the density conversion, a value of matrix density (ρma) of 2.65 g/cm³ was used. For the sonic log, the conversion was made using a matrix transit time of 55 μsec/ft.

Log responses of porosity in the density log of shales in the Lagoa Feia Formation clearly showed differences in log readings for organic-rich (source) and lean shales (Fig. 43). The same kind of well-log response was defined through the plot of sonic porosities versus depth (Fig. 44) and the plot of neutron porosities versus depth (Fig. 45). In all plots the "porosity" values of lean shales followed a trend of decreasing values with depth.

Considering the mineralogic complexity that characterizes the Lagoa Feia Formation, the correlation of decreasing porosities with depths is high as shown by the correlation coefficients above 0.7 (within sets of 163 samples) in each one of the plots (Figs. 43, 44, and 45). This fact is obviously explained by compaction effects on the shales, as discussed above.

The range of depths in which the log readings were selected for this study is very large. Because of the compaction effects shown by the trend of porosities followed by the lean shales, corrections for compaction in the
Figure 43. Density porosities (for $\rho_{\text{ms}} = 2.65$ g/cm$^3$) of shales within the Lagoa Feia Formation.
Figure 44. Sonic porosities (assuming $\Delta t_{ma} = 55$ $\mu$sec/ft) of shales within the Lagoa Feia Formation.
Figure 45. Neutron porosities of shales within the Lagoa Feia Formation.
porosity logs proved to be necessary, in order to compare properly the magnitude of each anomaly caused by different TOC amounts. Corrections for compaction were made by using the porosity versus depth regression equation for the lean shales in each log. All porosity values were "transported" to a datum of 1800 m, and then all the assumed compaction effects were removed from the absolute value of porosity registered at each level.

Another factor observed on porosity log readings in organic-rich rocks was that the difference between relative porosities defined by the neutron log and the density log was small compared to the lean shales (Fig. 46). This fact is explained by the variation in the mineralogical composition associated with the anoxic depositional environments of organic-rich rocks, with smaller amounts of clay minerals. As noticed by Mendelson and Toksöz (1985), source rocks have generally low water contents. Having smaller relative percentages of clay minerals, which are the ones responsible for holding water between their lattices, it is understandable why these lower water contents and why "porosities" on the neutron do not increase as in the density, and in consequence the quantity $\phi_n-\phi_d$ decreases in organic-rich rocks. Statistically significant differences in the populations of log readings was found in these values
Figure 46. Differences in relative "porosities" from neutron and density logs in lean and in organic-rich shales. Values of this difference tend to decrease in organic-rich shales (A) when compared with lean shales (B), because of changes in mineralogic contents. Well log is from a well located in the southern portion of the basin.
of $\phi_n - \phi_d$ (Fig. 47). In parallel, better borehole conditions were systematically observed in organic-rich shales, when compared to lean shales. Normal shales usually yield bad borehole walls, developing cavings because the clays absorb water from the drilling mud, expand, and cause weaknesses on those walls. Therefore, those better borehole conditions confirm the mineralogical changes towards a lower clay content in the organic-rich rocks of the Lagoa Feia Formation.

**Gamma-Ray Logs**

The distributions of gamma-ray values of organic-rich and lean shales were studied through histograms (Fig. 48) and shown to be from two statistically different populations. Lean shales showed average values slightly smaller than the organic-rich shales.

Gamma-ray values are a summation of contributions of the several natural radioactive isotopes. The main contributors in sedimentary rocks are $^{232}$Th, $^{238}$U, and $^{235}$U and their radioactive series (daughters) and $^{40}$K. Other radioactive isotopes are typically very modest contributors and may generally be neglected (Dypvik and Eriksen, 1982). Some approaches have been developed to connect the measured
Figure 47. Differences between neutron and density porosities for lean and organic-rich shales of the Lagoa Feia Formation. Statistical tests define different populations.
Figure 48. Gamma-ray values of lean and organic-rich shales within the Lagoa Feia Formation. Statistical tests revealed that they are from different populations although means ($\bar{x}$) and standard deviations ($s$) are relatively close.
natural gamma activity to the amounts of U, Th, and K (usually as K₂O) in different formations. Relationships between the units have been estimated by plotting calculated activity from U, Th, and K₂O values (in cpm/Kg, counts per minute per kilogram) against API units from available gamma-ray logs. Some disagreement still exists in these relationships. While R. Wendlandt (personal communication) recommends a simplified relationship represented by:

\[ \text{API} = 16 \text{ K (')} + 8 \text{ U (ppm)} + 4 \text{ Th (ppm)}, \]

Dypvik and Eriksen (1982) developed the following expression:

\[ \text{API} = 4.8 \text{ U (ppm)} + 4.8 \text{ Th (ppm)} + 19.2 \text{ K₂O (')}. \]

Furthermore, according to Eslinger and Pevear (1988), who published a relationship developed by E. Witterholt, the values registered in the log are defined by the following equation:

\[ \text{API} = 16.5 \text{ K (')} + 7.48 \text{ U (ppm)} + 1.43 \text{ Th (ppm)}. \]

Even with some disagreement, all of these relationships show that small increases in ppm of thorium and, in some cases, even smaller amounts of uranium will always cause significant deflections in the gamma-ray curve. Reported
concentrations of these natural radioactive elements in the "North American shale composite" (NASC) are: U = 2.6 ppm, Th = 12.3 ppm, and K₂O = 3.8 % (Gromet et al., 1984), while other authors refer to an "average shale" with very similar composition: U = 4 ppm, Th = 12 ppm, and K₂O = 3.6 % (Dypvik and Eriksen, 1982; Autric and Dumesnil, 1985). Therefore, these "average shales" usually have different levels of contributions from K₂O (~ 50 %), from Th (25 to 35 %), and from U (10 to 25 %), being the one from uranium commonly the lower one.

Assuming that the increase in values observed on the gamma-ray readings in organic-rich shales of the Lagoa Feia Formation (18 API, in average) is due to the increase only in uranium associated with organic carbon, an average increase only between 2 and 3 ppm of uranium occurs in this formation. These values are in remarkable contrast to what is observed in marine source shales, in some cases called "hot shales", with average increases of about 20 ppm (Autric and Dumesnil, 1985), usually in the range of 15 to 60 ppm (Fertl, Chilingar, and Yen, 1987). Examples exist from good marine source rocks, such as the Bakken Formation in the Williston basin, which show increases of 50 to 70 ppm (Schmoker and Hester, 1983) (Fig.49), or the Devonian shales of the Appalachian basin, which show increases of 25 to 30
Figure 49. Comparison of gamma-ray values on a marine sequence (a) in the Bakken Formation in the Williston basin and on a lacustrine sequence (b) in the Lagoa Feia Formation ((a) is modified from Schmoker and Hester, 1983; (b) is from a well located in the Badejo High area).
ppm (Schmoker, 1981). In "hot shales" from the North Sea, extreme enrichments of 144 ppm in uranium are reported (Dypvik and Eriksen, 1982). In the Meade Peak Member of the Phosphoria Formation, southeastern Idaho and western Wyoming, values between 43 and 80 ppm of uranium are observed (Desborough and Poole, 1983) associated with organic carbon amounts between 6.2 and 12.8 %, although in this rock unit P$_2$O$_5$ contents are usually high (between 8.6 and 26.1 %). As illustrated by this last example from the Phosphoria Formation, enrichments in uranium in source rocks are not always associated with only organic matter, but also with phosphatic skeletal debris as shown by several studies (Landis, 1962; Ramsen, Dickson, and Meakins, 1982; Everhart, 1983). Apatite is the main carrier of uranium in phosphate, and it is a common mineral in shales and limestones in the form of phosphatic nodules, concretions, and fossil replacements (Everhart, 1983).

Therefore, in some cases, high uranium concentrations in source rocks may occur associated with phosphatic debris. This association may explain why some authors have reported high concentrations of uranium in the sediments of the Green River Formation, Utah, Colorado, and Wyoming. Autric and Dumesnil (1985) reported values between 10 and 200 ppm, while values slightly above 100 ppm were observed by Mott
and Drever (1983). These high values may be associated with phosphatic material or secondary enrichment processes (R. Wendlandt, personal communication). Accordingly, Desborough, Pitman, and Huffman (1976) measured concentrations from 4.2 to 8.1 ppm of uranium in oil-shale beds in the Piceance basin, Colorado, and Uinta basin, Utah. Swanson (1960) reported a comparable range of 3 to 13 ppm, while Cook (1973) refers to only 0.99 ppm of uranium in a composite sample of the Mahogany ledge, which is the richest level in organic carbon within the Green River Formation.

The low uranium concentrations found in the Lagoa Feia Formation are probably due to the high solubility of uranium. In lacustrine or other continental environments the tendency is to have low uranium concentrations because most of it is transported in solution by the rivers to the ocean. The sediments of the Lagoa Feia Formation were deposited in lacustrine basins that were open for some periods of time, like the ones presently observed in east Africa. This fact may explain their low uranium concentrations.

In accordance with these observations in the Lagoa Feia Formation, which parallel most of the ones in the Green River Formation, Fertl, Chilingar, and Yen (1986) stated that uranium enrichment in organic-rich rocks is
particularly true for marine environments, whereas lacustrine source rocks appear to have no excessive gamma-ray activity, mainly due to the scarcity or absence of uranium ions in fresh-water environments. Furthermore, Meyer and Nederlof (1984) stated that plankton absorb uranium ions that are generally present in sea water together with other trace elements. Uranium is, thus, concentrated in marine source rocks, in contrast to lacustrine source rocks, where high anomalies on gamma-rays are absent owing to the scarcity or absence of uranium ions in freshwater.

**Resistivity Logs**

Compared to the porosity logs, resistivities showed a poorer correlation with depth for the lean rocks (Fig. 50), and did not make a clear differentiation of source from non-source rocks, especially at lower depths. This fact is in accordance with findings of other authors, who established better correlations of the variable resistivity with the maturation levels of the source rocks (Meissner, 1978; Smagala, Brown, and Nydegger, 1984; Mendelson and Toksöz, 1985; Fertl, Chilingar, and Yen, 1986). This aspect is discussed below in more detail.
Figure 50. Resistivity values of shales within the Lagoa Feia Formation.
Comparison with the Approach of Meyer and Nederlof

Meyer and Nederlof (1984, 1986; Aljawadi, 1986) developed an approach to characterize source rocks from well-log readings, which was calibrated in their work with 169 samples from nine different basins around the world, although with data from 15 wells only. To characterize potential source rocks, those authors created two crossplots of temperature-corrected resistivity, the first one versus sonic transit time, and the second one versus bulk density (Fig. 51).

In their approach, independent direct measurements on cores or cuttings (recovered from the same intervals) discriminate between non-source rocks and source rocks including coals. The cutoff adopted between source rocks and non-source rocks was the measurement of 1% weight of organic carbon. On Figure 51 the discriminant function (D) defined for the separation of non-source from source rocks is represented by a straight line in each plot. In the coordinate system chosen for the crossplots created by Meyer and Nederlof (1984), source rocks are represented on one side of a given experimental straight line, and the non-source rocks on the other side. The straight line has a sort of absolute definition, and apparently it does a better
Figure 51. Results obtained by Meyer and Nederlof in the discrimination of source from non-source rocks in nine basins around the world (modified from Meyer and Nederlof, 1984).
job for zones with higher resistivities (mature source rocks). According to Autric and Dumesnil (1985) the plots may show some problems on immature source rocks.

The approach developed by Meyer and Nederlof (1984) was applied for the organic-rich shales of the Lagoa Feia Formation. The results (Fig. 52) were not as good as the characterization of source rocks developed in this study. The indication in both plots was that discriminant functions different from the ones developed by those authors would be more precise in the characterization. Furthermore, the approach is only qualitative, and rocks are only classified as source or lean, without indications of TOC amounts. Meyer and Nederlof studied only marine source rocks, and as discussed earlier, these rocks have several other differences from the lacustrine source rocks. The poor characterization obtained through the application of their approach is very important, indicating that unique calibrations of log readings have to be obtained for each stratigraphic sequence. In fact, Hussain (1987) used a very similar approach to characterize source rocks existing in the state of Kuwait. He just added a third crossplot of gamma-ray readings versus temperature-corrected resistivities but had to derive different equations for each one of the plots used, based on peculiar characteristics
Figure 52. Meyer and Nederlof approach applied on shales of the Lagoa Feia Formation. A better job of discrimination would be done by different discriminant functions represented by the dashed lines (which were not defined analytically, but only graphically in the plots).
of the rock sequence that he studied.

Therefore, local characteristics of rock sequences will always have to be taken into account, since logs will be sensitive not only to the amounts of TOC but also to the type of organic matter and particular mineralogic characteristics of each sequence. These aspects strongly illustrate the meaning of calibrating logs with other measurements performed in each stratigraphic sequence. As stated by Moss and Harrison (1986), and also observed by Herron (1987) this is the only way of obtaining statistically significant greater amounts of geologic information.

**Statistical Treatment of Data**

The log responses of organic-rich lacustrine shales existing in the Lagoa Feia Formation were studied with the help of statistical treatment of data. Intervals of uniform and high-quality log readings, that had in parallel geochemical measurements of their characteristics in laboratory, were analyzed. Used were 163 intervals, although more than 1,600 measurements of TOC were available. Therefore, only about 10% of the database of TOC
measurements were correlated with log readings considered reliable enough to be used in the generation of the interpretation model for the source rocks. Crossplotting techniques, initially applied on the data, helped in the definition of trends of variability of the overall properties of these rocks, applicability of corrections, and statistical techniques more suitable for being used. In order to use statistical methods appropriately, the data were normalized through transformations before the application of the statistical techniques.

**Transformation of Data**

After the data were corrected for compaction, some of the raw data of log-readings presented distributions that were significantly different from the normal distribution (Fig. 53).

According to Johnson and Wichern (1982), if normality is not a viable assumption, the alternative is to ignore the findings of the normality checks and proceed as if the data were normally distributed. However, according to those same authors, this practice is not recommended since, in many instances, it could lead to incorrect conclusions. A second alternative is to make non-normal data more "normal looking" by considering transformations of the data.
Figure 53. Distributions of raw data of density, sonic, and TOC values in organic-rich and lean shales of the Lagoa Feia Formation.
Following these considerations, transformations were applied to some of the variables before the application of statistical treatment to the data in this study. Transformations are nothing more than a reexpression of the data in different units. For example, when a histogram of positive observations exhibits a long right-hand tail (like the values of TOC, $Q_b$, and $\Delta t$, from shales of the Lagoa Feia Formation -- see Fig. 53), transforming the observations by taking their logarithms or square roots will often markedly improve the symmetry about the mean and the approximation to a normal distribution. In another words, the new units provide more natural expressions of the characteristics being studied.

Power transformations (Carroll and Ruppert, 1984) were initially tried and did not improve the approximation to the normal distribution as significantly as log transformations for the variables $\phi_d$, $\phi_s$, $\phi_n$, and TOC. These log transformations made the distributions of these variables more symmetrical, and reasonably close to the normal distribution. Furthermore, if the Central Limit theorem is taken into account in an approach similar to the one chosen by Whitman (1986), the general conclusions of this work will not depend heavily on the exactness of the assumption of normality of these transformed variables. After all
variables had distributions close to normal (Fig. 54), the statistical treatment of data was undertaken.

**Statistical Techniques**

Two different approaches were taken in the statistical treatment of data, one qualitative and the other quantitative, and in consequence two different multivariate techniques were applied. In the first one, the qualitative approach, discriminant analysis was employed aiming to discriminate good source rocks (TOC>2%) from lean shales (TOC<0.5%). In the second approach, multivariate regression analysis was used aiming to generate quantitative predictions of TOC values for all rocks, using all sets of log readings. STATPAC, was used in this phase of the work.

**Discriminant Analysis.** On discriminant analysis, a linear combination of variables is found, which produces the maximum difference between two or more previously defined groups (Davis, 1986). This function can then be used to allocate new samples of unknown origin to one of the original groups. Therefore, the technique constructs, in an optimal way, a linear combination of the variables involved that is then used for classification (Kleinbaum, Kupper, and
Figure 54. Normalized distributions after applications of log functions to the data from the porosity logs and Toc measurements in laboratory.
Muller, 1988).

As discussed before, the shales of the Lagoa Feia Formation were divided in three groups. In order to maximize the differences between source (TOC>2.0%) and lean rocks (TOC<0.5%), only these two groups were considered in the generation of the discriminant function. Transformed and corrected values of log readings in the sonic, density, neutron, and gamma-ray logs were used as variables in the discrimination. These variables were chosen because, as discussed previously, are the ones with potential for the characterization of TOC amounts in the shales of the Lagoa Feia Formation. Resistivity values were not used because of the poor correlation of this variable with TOC amounts. According to observations in the $\phi_n-\phi_d$ values in organic-rich shales when compared to lean shales, this quantity was considered an additional variable in the statistical treatment of the data. Log readings that correlated with TOC<0.5% (lean shales) were in number of 60, whereas 65 sets of log readings correlated with sourcè rocks (TOC>2.0%).

A discriminant function was defined by STATPAC, after the treatment of log data of the two previously defined groups of lean and organic-rich shales, and it was represented by:
DISC = 0.0365x(GR) + 91.378x(log $\varnothing_d$) - 94.64x(log $\varnothing_n$) 
+ 12.595x(log $\varnothing_s$) + 1.197x($\varnothing_n$-$\varnothing_d$) - 8.299

The discriminant function defined by STATPAC provided an excellent discrimination of lean from organic-rich shales (Fig. 55). Only one sample with TOC<0.5% was classified as source. Three samples with TOC>2.0% were grouped with the barren rocks.

Rocks with TOC values in between 0.5 and 2.0% -- in the group initially classified as marginal rocks, and represented by 38 sets of log readings -- fell in both areas, but interestingly enough, those with TOC amounts below 1.0% fell in the area of lean rocks with the exception of one sample in 15. Those with TOC above 1.0% were classified as source in the majority of cases (15 in 23). Therefore, the discriminant function did an excellent job not only in grouping rocks with more than 2.0% TOC separately from those with less than 0.5% TOC, but also a very good job in the separation of rocks with more than 1.0% from the ones with less than 1.0% TOC.

Multiple Regression.- Multiple regression corresponds to a polynomial curve fitting. It is an extension of straight-line regression analysis, which involves only one
Figure 55. Two-dimensional graphic results obtained through STATPAC with the application of discriminant analysis to the database of log readings.
independent variable, to the situation where there is more than one independent variable to be considered (Kleinbaum, Kupper, and Muller, 1988). Although both, discriminant analysis and multiple regression attempt to describe, by using a linear model, the relationship between a dependent and several independent variables, discriminant analysis has a primary purpose of discrimination -- a qualitative approach -- whereas multiple regression has the primary purpose of prediction -- and therefore, a quantitative approach.

STATPAC results for the multiple regression generated an equation for the prediction of TOC amounts from well-log readings, using exactly the same variables used in the discriminant analysis. The program defined the following function for the prediction of TOC amounts:

$$\log \text{TOC} = 0.0253x(\text{GR}) + 5.146x(\log \varnothing_d) - 4.625x(\log \varnothing_n)$$
$$+ 0.3424x(\log \varnothing_s) + 0.0683x(\varnothing_n - \varnothing_d) - 1.0325$$

In multiple regression, the relative effectiveness of the independent variables as predictors of the dependent variable can be determined (Davis, 1986). However, this determination cannot be obtained from a direct examination of the regression coefficients, because their magnitudes are dependent upon the magnitudes of the variables themselves.
The approach to standardize the partial regression coefficients, by converting them into units of standard deviation, presented by Davis (1986) and represented by:

\[ B_k = b_k \frac{s_k}{s_Y} \]

where

- \( B_k \) = standard partial regression coefficient,
- \( b_k \) = partial regression coefficient,
- \( s_k \) = standard deviation of the variables \( X_k \) (independent variables), and
- \( s_y \) = standard deviation of \( Y \) (dependent variable),

was used in the interpretation of the multiple regression equation derived by STATPAC for the prediction of TOC amounts for the Lagoa Feia shales. Table II presents the results of this analysis.

The results presented on Table II suggest that the strongest indicator of the TOC amounts for the Lagoa Feia sequence is the density log. Therefore, pyrite contents, which tends to confound the indications of TOC by the density logs, are not an important factor in the organic-rich shales of the Lagoa Feia Formation. Furthermore, although in this sequence differences in gamma-ray readings between organic-rich and lean shales are subtle, statistically, the gamma-ray log does a reasonably good job
TABLE II
Standardized Regression Coefficients

<table>
<thead>
<tr>
<th>Variable</th>
<th>( b_k )</th>
<th>( B_k )</th>
<th>relative effectiveness (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamma-ray</td>
<td>0.0253</td>
<td>0.97352</td>
<td>28.7</td>
</tr>
<tr>
<td>( \log \varnothing_d )</td>
<td>5.146</td>
<td>1.3838</td>
<td>40.8</td>
</tr>
<tr>
<td>( \log \varnothing_n )</td>
<td>4.625</td>
<td>0.63632</td>
<td>18.8</td>
</tr>
<tr>
<td>( \log \varnothing_s )</td>
<td>0.3424</td>
<td>0.0767</td>
<td>2.3</td>
</tr>
<tr>
<td>( \varnothing_n - \varnothing_d )</td>
<td>0.0683</td>
<td>0.322</td>
<td>9.5</td>
</tr>
</tbody>
</table>

in the characterization, being the second strongest indicator of TOC amounts.

The values of TOC calculated using the equation provided by the multiple regression technique showed high correlation with laboratory measurements of TOC. From the value of \( r=0.77 \) (Fig. 56), encountered for the 163 sets of log readings used in the study, the correlation coefficient for the whole population of log readings can be estimated to be within 0.68 and 0.83 (with 95% of confidence), using the method of calculation of confidence intervals shown by Dixon and Massey (1969). Contrarily to what is suggested by Herron (1987), the multiple regression equation performs a
Figure 56. Comparison of TOC amounts predicted by the multiple regression function and the TOC amounts measured in laboratory for samples at equivalent depths.
very homogeneous job in the predictions of TOC amounts for the good (TOC>2.0%) and for the marginal source rocks (0.5%<TOC<2.0%).

Application of Results

Using the facilities provided by ES-LOG, programs were generated to insert the discriminant function and the equation for prediction of TOC as an output, in all log sequences available on tape in the Lagoa Feia Formation. Continuous values for the discriminant and TOC amounts were then obtained (Fig. 57), in most cases with good matches with laboratory measurements. In fact, excellent matches with laboratory data cannot be expected in all logged sequences because several aspects have to be considered in this comparison, such as:

a) the level of resolution of techniques being compared. The volume of sample investigated by core measurement, or the ones performed on cuttings, is much smaller than the logging measurements (Mendelson and Toksöz, 1985). Figure 58 shows differences in vertical resolution from cores to logs, and from those
Figure 57. Example of results obtained for continuous calculations of TOC and discriminant scores for intervals with presence of source rocks. This result is from a well located in the western portion of the basin.
Figure 58. (A) Averaging effects on readings of logs with different vertical resolution. (B) Comparison of different vertical resolutions of cores, logs, and seismic sections (combined and modified from (A) Doveton, 1986, and (B) Richardson, Sangre, and Sneider, 1987).
to seismic. The spatial resolution of the logging probe is generally limited by a characteristic physical distance of measurement path. Properties varying in a scale finer than that will be averaged into a larger investigative volume. In many cases, this averaging may be a desirable side effect. It does, however, present a problem if high log-core correlations are the targeted goals (Mendelson, and Toksöüz, 1985). This may, in fact, be the problem encountered by Mann, Leythaeuser, and Müller (1985), who did not get good results on trying to correlate 75 laboratory measurements of amount and quality of organic matter, at 10 and even 1 cm intervals in a 16.10 m core, with natural gamma ray spectrometry, sonic, density, induction, and proximity logs,
b) the variations of TOC amounts within an organic-rich rock. A miscorrelation between petrophysical data can occur because of the thin layer effect. An individual layer, from which samples for chemical analyses were taken, may be organically lean, even though
intcalated in a source-rock sequence and vice-versa (Fig. 59),

c) the amounts of sample used on geochemical analyses. Geochemical analyses used in this study, were obtained from cores and cuttings. In all cases, TOC measurements were performed in only 5 g of the whole sample of core or cuttings, whereas for Rock-Eval pyrolysis even smaller amounts of samples were used (200 mg), and

d) the variations in depths of results from laboratory when compared to well-log results. Because most of the calibrations of log readings in this study was done through measurements on cuttings, some variable lag of values of geochemical analysis from results on log readings have to be expected. The variability on lag magnitudes will depend mainly on drilling parameters used in each well and depths of each measurement.

The results obtained using the functions defined through the statistical treatment of the data could be tested in all key wells in the basin, and they were especially good in the discrimination between source rocks
Figure 59. Photomicrograph of a organic-rich shale within the Lagoa Feia Formation. Variations in amounts of organic carbon in the different rock laminae are common. Bar in the photo is 5 mm in length. Photomicrograph is a small-scale view of the same thin section from which parts are presented on Figure 41.
and non-source rocks. Facilities in the ES-LOG permitted the application of these results only on sections of shales through the calculation of functions only on levels with higher gamma rays. This was done as a step in the program introduced in the ES-LOG for the generation of these results. Another step in the same program allowed to cut the presentation of results in intervals with poor borehole conditions. A combination of readings of the DRHO and caliper curves were the input necessary for the evaluation of the borehole conditions by the program. Additional examples of evaluation of the source-rock potential of shales of the Lagoa Feia Formation are presented in the Appendix IV.

In the results obtained from the log readings, more complete information is shown. The thickness of each level, its richness and trends in variation in richness, which constitute a group of much more complete information when compared with the scattered values defined in laboratory (Fig. 60), are easier to depict. As stated before, this kind of information, generated through well-logs in this study, is fundamental in volumetric calculations for oil prospects.
Figure 60. Comparison of results obtained from log analysis with scattered laboratory results. This results are from a well located in the western portion of the basin.
Cyclicity Supported by Well-Log Responses

The geologic validity of the results, obtained in the continuous evaluation of source rocks through well-log responses, were somewhat confirmed by the logic shown in the variability of source-rock quality defined by the functions in most cases. Peculiar characteristics of the lacustrine sedimentation showing shallowing-upward cycles were commonly observed in the results. Usually, better source rock conditions were shown in the basal portions of the cycles, which are possibly related to the existence of stratified columns of water following deepening events, with the deposition of richer source rocks in the anoxic bottoms of the lakes. Interestingly enough, these cycles are not detected by the gamma-ray alone, which is the log used for the definition of cyclicity in traditional well-log interpretation (Fig. 61). In this case, the strength of the density log on the definition of TOC amounts in the Lagoa Feia Formation was the factor responsible for the definition of the cycles in the discriminant and multiple regression functions.
Figure 61. Cyclicity observed in the results of the evaluation of source rocks. Although the cycles are not evidenced by the gamma-ray log, they are easily recognizable in these results, which are from a well located in the central portion of the basin.
Resistivity as Maturity Indicator

As discussed earlier and seen on Figure 50, the correlations of resistivity values and organic carbon contents for the shales in the Lagoa Feia Formation were not as good as the ones observed in the other logs of the suite used in this study. According to several other authors (Meissner, 1978; Meyer and Nederlof, 1984; Smagala, Brown and Nydegger, 1984; Mendelson and Toksöz, 1985; Fertl, Chilingar, and Yen, 1986), the correlation of these measurements is much better with increasing maturity levels of the organic-rich shales in the unit.

Increases in resistivity are predicted to be correlated to maturity levels, because the main factor increasing resistivity is not only the presence of organic carbon, but mainly the increasing presence of oil in the source-rock interstices after it penetrates the oil window (Fig. 62). With increasing maturity, the resistivity of a source rock increases by a factor of ten or more (Meyer and Nederlof, 1984), and then, resistivity-derived measurements can be used as indicators of maturity levels of source rocks. Resistivity is a better maturity indicator than a TOC predictor. This happens because not only TOC contents will increase resistivity, but also the different amounts of oil
Figure 62. Resistivity increase due to maturity of the source rock (combined and modified from Tissot, 1984 and Meissner, 1978).
in the rock at each level of maturity will affect more significantly the readings on these logs. Furthermore, and besides TOC amounts, the type of kerogen is another important factor; in fact, equivalent amounts of type I and type III kerogen will generate completely different fluids in the source rocks at the same maturity level.

After corrections for compaction, resistivity ratios, among lean and organic-rich rocks in the same sequence, were calculated in the Lagoa Feia Formation. Using the 45 vitrinite reflectance measurements available in the database, a correlation coefficient was calculated (Fig. 63), and from there the correlation coefficient for the whole population can be estimated to be within 0.51 and 0.84 (with 95% confidence), again using the method of Dixon and Massey (1969). Before disregarding these resistivity ratios as useful maturity indicators in this sequence, several other factors have to be considered.

First of all, the kerogen type in the Lagoa Feia Formation is dominantly type I (algal lacustrine origin). The modified van Krevelen diagram shown on Figure 64 is from more than 300 Rock-Eval pyrolysis that presented productivity indices higher than 0.5 mg of hydrocarbon per gram of rock sample, or in another words, more reliable results because of the higher quantity of hydrocarbon
Figure 63. Vitrinite reflectance versus resistivity ratios between source and lean shales in the Lagoa Feia Formation.
Figure 64. Kerogen types in the Lagoa Feia Formation. This modified van Krevelen diagram was obtained from the results of more than 300 Rock-Eval pyrolysis in the Lagoa Feia Formation.
produced in the analysis. As can be seen on Figure 64, type I kerogen is the dominant and some mixings with type III occur (type II is absent because it is a non-marine sequence). Because of the dearth of type III kerogen in the sequence, vitrinite particles for maturity-level measurements are very rare. In fact, in the database used in this study with more than 1,600 TOC measurements, only 45 vitrinite values were available. Therefore, the calibration of the log readings was not possible in the same fashion made for the other geochemical measurements.

In addition, in rock sequences where type I kerogen is dominant, $T_{\text{max}}$, also used besides vitrinite reflectance, is commonly a poor maturity indicator. This happens because the transformation of type I kerogen to hydrocarbons, compared to the other kerogen types, occurs within a very narrow range of temperatures (Fig. 65). Accordingly, this poor correlation was confirmed in the values of $T_{\text{max}}$ obtained for the shales of the Lagoa Feia Formation (Fig. 66), in which the indications were always towards maturity levels lower than the ones revealed by vitrinite reflectance measurements.

Resistivity ratios as shown here, are potentially useful indicators for maturity levels in this section, especially when compared to the indications from $T_{\text{max}}$ and
Figure 65. $T_{\text{max}}$ responses for different kerogen types. The transformation ratios for different types of kerogen occur at different ranges of temperature (modified from Waples, 1987).
Figure 66. $T_{\text{max}}$ values for more than 300 samples in the Lagoa Feia Formation.
when the scarcity of vitrinite particles available for measurements is taken into account. These ratios may become very useful after a better calibration with more data from vitrinite reflectance in the sequence becomes available in the future.

**Final Results**

Figure 67 shows the results obtained through the applications of the statistical techniques to another well. The resistivity curve is added and then ratios between resistivities of source rocks and lean rocks can be calculated. Plate V show the same results, in color, from another well. Comparing the results of the resistivity ratios, calculated for the shales on Figure 67, with the trend shown on Figure 63, the maturity level of the source rocks in that sequence can then be ascertained.

Therefore, analyzing the results obtained from the application of discriminant analysis and multiple regression, as seen earlier, in conjunction to resistivity measurements, the following geochemical characteristics, within confidence intervals as discussed before, can be ascertained for each level:
Figure 67. Association of results from discriminant analysis and multiple regression with resistivity values. A reasonably complete geochemical evaluation can then be performed. This result is from the same well interval shown on Figure 42.
a) the presence or absence of good source-rock potential,
b) the richness in organic carbon,
c) the thickness of the organic-rich levels,
d) the trend of variation in richness of organic carbon in each level, and
e) the level of maturity that can be expected for the source rock.

In another words, conditions are created for volumetric calculations of hydrocarbon prospects in any area of the basin, because the geographic distribution of the organic-rich levels can also be ascertained using other subsurface techniques.

An additional factor to be considered in the evaluation of the methodology developed in this work is the cost of geochemical measurements performed in laboratory. Continuous evaluation of rock sequences through laboratory techniques, although possible, would be prohibitive because of the costs involved. The only way of having this continuous evaluation seems to be through well-calibrated well logs. Furthermore, if applied in advance on previously known rock sequences, the source-rock evaluation through well logs may become an excellent screening technique in the definition of intervals where it is worth to invest
money in a more detailed evaluation of the source rocks through laboratory techniques.

Table III shows a sequence of procedures to be followed in the well-log evaluation of the source-rock potential of the shales occurring in the middle portion of the Lagoa Feia Formation, according to the approaches developed in this study.

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<td>1</td>
<td>Transformation of log readings in porosity values. - Density and sonic readings have to be transformed in equivalent porosity values using $\rho = 2.65 , g/cm^3$, and $t_m = 55 , \mu sec/ft$.</td>
</tr>
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<td>Corrections for compaction. - Density, sonic, and neutron porosities have to be corrected for a datum of 1800 m, using the regression equations shown on Figures 43, 44, and 45 respectively.</td>
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<tr>
<td>3</td>
<td>Calculation of the discriminant. - Using the equation shown on page 186 the discriminant value of the level is calculated.</td>
</tr>
</tbody>
</table>
Calculation of TOC.- Using the equation on page 188 the TOC amount in the level is predicted.

Definition of source-rock potential.- Highly positive discriminant values are indicative of good source-rock potential. TOC values above 2 % increase the strength of indications of good source-rock potential.

Definition of maturation level.- Ratios between resistivities of organic-rich and lean on levels close to the level that is being evaluated are calculated. Using the chart shown on page 205, the maturation level of the source rock is predicted.

This method of source-rock evaluation was developed for the middle portion of the Lagoa Feia Formation and can give geochemical information only for this portion of this rock sequence, within confidence limits and probability levels as discussed above. Other considerations involving limitations inherent to the method developed in this study will include:

a) the basic assumptions in the development of the method are the ones on how the presence of organic carbon may affect log readings.
Research in this area has been continuously developed and may change some of these assumptions,

b) the steps followed for the development of this method for this lacustrine sequence may be followed for other rock sequences and should furnish similar results if reasonably large databases are available,

c) this method of evaluation can be applied to any rock sequence or other portions of the Lagoa Feia Formation just to assess source-rock potential. Better results are expected on lacustrine sequences developed on similar geologic settings. Obviously, in any case, the confidence limits for values obtained will not be maintained,

d) some mineralogic changes occurring on shales may affect the log readings in an opposite way of the organic carbon, and in some levels, the presence of organic carbon may be masked,

e) again, differences on vertical resolution of different techniques for measuring geochemical parameters are always important to bear in mind when comparing results.
CONCLUSIONS

The conclusions of this work fall into four categories:

A) Regarding the general evaluation of oil-reservoirs and characterization of source rocks from well-log readings:

a) the evaluation of unconventional reservoirs, such as the coquinas of the Lagoa Feia Formation, is significantly improved when particular properties of these rocks, described in cores, are related to specific log readings. Models of interpretation can then be adjusted accounting for these particular properties and will furnish better results,

b) the use of well-log readings for the definition of geochemical properties of source rocks is an excellent complement for the commonly expensive geochemical techniques in use. Log readings properly calibrated, with particular characteristics of rock sequences, give invaluable information for volumetric calculations of oil prospects, especially when combined log readings are used. They are reliable trend indicators of thickness and
richness, properties not commonly detected by punctual laboratory measurements. When properly calibrated, they seem to work adequately not only for good source rocks (TOC>2.0%) but also for the marginal ones (0.5%<TOC<2.0%),

(c) a preliminary geochemical evaluation using well-log readings is an excellent screening technique in the design of an effective program for source-rock evaluation,

(d) resistivity-derived measurements for organic-rich levels, when properly related to the geologic characteristics of rock sequences, can be reliable maturity indicators, especially in sequences where terrestrial material is rare or absent,

(e) excellent matches of source-rock well-log evaluation with laboratory measurements cannot always be expected, because the resolution of the techniques being compared is completely different. The averaging effect of log readings has always to be considered,

(f) in the calibration of log responses of source rocks, it is important to consider corrections
for compaction effects, especially if dealing with large range of depths in the log measurements,
g) the difference $\phi_n - \phi_d$ can be used as an indicator of the presence of organic carbon on source rocks, because it is probably related to variations in mineralogical contents in these rocks towards smaller clay contents,
h) due to the mobility of uranium, and its consequent scarcity on continental waters, source rocks on lacustrine sequences will not present strong gamma-ray anomalies as commonly observed on marine source rocks,
i) presence of early silica cements in rocks deposited on high-pH environments is an important factor to be considered. These high-pH environments are mainly related to continental deposition associated with mafic and ultramafic rocks in the source areas.

B) Specific to the coquina reservoirs in the Lagoa Feia Formation:
   a) water-free production from coquina reservoirs are expected only in intervals with water saturations below approximately 30%,
b) bulk volumes of water are extremely low in oil-producing zones due to the unusual pore structure of the coquinas,
c) more realistic values of water saturations are obtained using increasing cementation and saturation exponents in the Archie equation at lower porosities, also because of the vuggy porosities,
d) silica cements are important, especially in high-porosity coquinas, and have to be taken into account in the derivation of porosities from single logs.

C) Specific to the organic-rich lacustrine shales in the Lagoa Feia Formation:

a) density, gamma-ray, neutron, and sonic logs, in this order, are good indicators of the presence of organic carbon in these rocks,
b) although present, pyrite does not mask the detection of organic carbon by the density log,
c) uranium contents are, in average, 2 to 3 ppm higher in these rocks compared with lean shales, as revealed by readings on gamma-ray logs,
d) resistivity is a useful maturity indicator in this sequence due to the dearth of vitrinite particles for maturity-level measurements. The scarcity of vitrinite particles is related to the predominance of type I kerogen in the sequence. With more vitrinite reflectance measurements becoming available, a stronger correlation for the resistivity ratios among source and lean rocks and maturity levels is suggested to be tried,

e) discriminant analysis applied on readings of density, neutron, sonic, and gamma-ray logs proved to be a powerful technique in the discrimination between source and lean rocks. Multiple regression, applied to the same log readings, generated a function that estimates TOC amounts well correlated with laboratory results, within confidence intervals at 95% probability levels.

D) Related to other portions of the stratigraphic sequence of the Lagoa Feia Formation:

a) high porosities and low resistivities commonly registered in the lower portion of the Lagoa
Feia Formation are related to the presence of stevensite, a smectite-like mineral, because of the tendency of this mineral of absorbing, and in this case, retaining larger amounts of water,

b) low gamma-ray values in this same portion of the section are also related to the presence of these stevensites, because the precipitation of this mineral requires low K⁺ contents, and potassium is one of the elements responsible for the net of gamma-ray responses in all sequences,

c) volcaniclastic reservoirs are not always shaly as usually considered form gamma-ray and porosity log readings. In most cases, those log responses are related to minerals in the rock fragments that are the main components of these siliciclastic rocks in the sequence.
GLOSSARY

Illustrations involving well-log data presented in this work are related to information contained in continuous curves existing in the database or created through the use of ES-LOG. The meaning of each one of these curves, and when appropriate, how they were created, are listed below:

BVW - bulk volume of water calculated through ES-LOG for the reservoir rocks (it represents the product $\phi_e \times Sw$).

CALI - original caliper log registered in the well-logging operation.

CORTOC - punctual values of TOC (organic carbon contents) obtained in laboratory, measured on cores, and entered manually in the ES-LOG.

DISC - continuous values of the discriminant function defined by discriminant analysis applied on the log readings on source rocks through STATPAC and calculated by ES-LOG.

DISCØ - vertical line located at DISC=0 presented in the results obtained for the evaluation of the source rocks, just for comparison of results.

DRHO - original log of corrections in the density log registered in the well-logging operation.

DT - original sonic log registered in the well-logging operation.

DTS - sonic log filtered to have the vertical resolution matched with the deep induction, using function available in the ES-LOG.

GR - original gamma-ray log registered in the well-logging operation.
ILD - original deep induction log registered in the well-logging operation.

LLD - original log of resistivity in the laterolog deep registered in the well-logging operation.

NPHI - original neutron log registered in the well-logging operation.

NPHS - neutron log filtered to have the vertical resolution matched with the deep induction, using function available in the ES-LOG.

PSS - porosity values derived from the sonic log. It is calculated continuously by ES-LOG.

PXND - porosity values derived from the neutron-density crossplot and calculated continuously by ES-LOG.

RHOB - original density log registered in the well-logging operation.

RHOS - density log filtered to have the vertical resolution matched with the deep induction, using function available in the ES-LOG.

SW - water saturations calculated through ES-LOG using the approach developed in this work.

SWARCH - water saturations calculated through ES-LOG using the Archie equation with parameters commonly used on limestones and porosities derived from the density log.

SW30 - vertical line located at Sw=30\% presented in the results obtained for the evaluation of coquinas, just for comparison of values.

TOC - continuous values of TOC calculated by ES-LOG using the function defined by multiple regression of log readings through STATPAC.

TOCLAB - punctual TOC values obtained in laboratory, measured on cuttings, and entered manually in the ES-LOG.
TOC2 - vertical line located at TOC=2.0% presented in the results obtained for the evaluation of source rocks, just for comparison of values.
REFERENCES CITED


APPENDIX I

Additional Examples of Well-Log Responses of Coquinas

Figures 68, 69, 70, 71, and 72, represent additional examples of log responses in coquinas of the Lagoa Feia Formation in the Campos basin.

Well-log evaluation of the coquinas presented on these well intervals are shown on Appendix II.
Figure 68. Interval of coquinas showing predominantly medium to low resistivities at some levels, where porosities are extremely low. Well located in the central portion of the basin.
Figure 69. Extremely high-resistivity and low-porosity coquina interval. Especially between x700 and x750 m, gamma-ray values are not as low as usually observed in oil-productive coquinas. Well located in the central portion of the basin.
Figure 70. High gamma-ray, high-resistivity coquinas thinly interbedded with lacustrine shales. Well located in the central portion of the basin.
Figure 71. Low-resistivity, "High"-porosity coquinas. Same well interval presented on Figure 42 to exemplify log responses on lacustrine shales.
Figure 72. "Clean" coquinas (low gamma-ray values) showing predominantly high resistivities and low porosities. Well located in the central portion of the basin.
APPENDIX II

Additional Examples of Well-Log Evaluation of Coquinas

Figures 73, 74, 75, 76, and 77 represent additional examples of results obtained in the evaluation of the coquinas of the Lagoa Feia Formation using the approaches developed in this study.

Well-log responses of the coquina intervals shown in this Appendix were presented in the Appendix I.
Figure 73. Well-log evaluation of the coquinas presented on Figure 68. Water-saturated interval showing high BVW's towards the bottom. Sw's are not calculated on certain low-gamma-ray intervals because of bad borehole conditions.
Figure 74. Well-log evaluation of the coquinas presented on Figure 69. Interval between x750 and x800 m produced oil/water after stimulation. Interval between x690 and x700 m produced only water after stimulation.
Figure 75. Well-log evaluation of the coquinas presented on Figure 70. In these water-productive zones, differences on Sw values obtained through Archie and through the approach derived in this study are observed in the intervals x755/x772 m and x825/x835 m.
Figure 76. Well-log evaluation of the coquinas presented on Figure 71. High Sw values are calculated in the entire interval. BVW values are also high.
Figure 77. Well-log evaluation of the coquinas presented on Figure 72. Very low-porosity water-saturated coquinas. Significant differences in Sw values occur at x630/x633 m.
APPENDIX III

Additional Examples of Well-Log Responses of Shales

Figures 78, 79, 80, 81, 82, 83, 84, and 85, represent additional examples of log responses in shales of the Lagoa Feia Formation in the Campos basin.

Well-log, source-rock potential evaluation of shales shown on Figure 78 through 84 are presented in the Appendix IV.
Figure 78. Log readings on density, neutron, and sonic are very constant in this shale section, while gamma-ray values show more variation. Well located in the northern part of the basin.
Figure 79. Log readings on sonic, density, and neutron logs vary significantly in some levels in this well, which is located in the western portion of the Badejo High area. Resistivities are extremely low in the entire interval.
Figure 80. In this well, zones of anomalous readings on porosity logs are present at x410, x430, and x470 m. Except for the last one, these intervals are not detected by the gamma-ray curve. well located in the central portion of the basin.
Figure 81. Interbedded high- and low-porosity shales, presenting high resistivities, occur in the interval x210/x270 m. Well located in the central portion of the basin.
Figure 82. Shales occurring between X725 and X775 m present low resistivity and predominantly low gamma-ray values, well located in the Badejo High area.

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WELL NAME: LF26
Figure 83. Same interval presented in the examples of coquina evaluation (Figures 68 and 73). At x415 m, shales exhibit high gamma-rays and high resistivities.
Figure 84. Predominantly high-resistivity shales are presented in this shale section interbedded with coquina intervals. Well located in the central portion of the basin.
Figure 85. Remarkably high-porosity, high-resistivity, and high-gamma-ray values in a high-quality source rock in the interval x980/x015 m. Well located in the central portion of the basin.
APPENDIX IV

Additional Examples of Well-Log Evaluation of Shales

Figures 86, 87, 88, 89, 90, 91, 92, and 93, represent additional examples of the well-log, source-rock-potential evaluation of shales of the Lagoa Feia Formation along the Campos basin.

Well-log responses of shale intervals presented on Figures 86 through 92 in this Appendix are shown in the Appendix III.
Figure 86. Well-log, source-rock-potential evaluation of shales presented on Figure 78. Correlation of well-log results with laboratory measurements is very good in this section of predominant low source-rock potential.
Figure 87. Well-log, source-rock-potential evaluation of shales presented on Figure 79. Correlation is high with laboratory results, and a clear lag of about 5 m between results is observed in two points within the interval x970/x985 m.
Figure 88. Well-log, source-rock-potential evaluation of shales presented on Figure 80.
Equivalent good source potential are detected on thin layers at x10 and x40 m even with their completely different gamma-ray response.
Figure 89. Well-log, source-rock-potential evaluation of shales presented on figure 81. Interval of mature source rocks (see high resistivities on Figure 81) occurs at x210/x270 m (1.5%<TOC<4.5%).
Figure 90. well-log, source-rock-potential evaluation of shales presented on Figure 82. Low source-potential rocks occur between x725 and x775 m more or less in the same way as detected by laboratory results.
Figure 91. Well-log, source-rock-potential evaluation of shales presented on Figure 83. Predominantly marginal source rocks, even with some high resistivities as shown on Figure 83. Below x450 m, the results are almost absent because of bad borehole conditions.
Figure 92. Well-log, source-rock-potential evaluation of shale presented on Figure 84. This example just shows the usefulness of the well-log evaluation of source rocks. In this section, laboratory analyses were not available, but now its source rock potential can be assessed.
Figure 93. Bad borehole conditions prevented most of the evaluation of the source-rock potential below x875 m in this interval of well located in the southern portion of the Badejo High area.
APPENDIX V

Database Used in this Study

This appendix is presented in the form of a table where the database used in this study is summarized. On the table, some of the column headings were replaced by numbers, in order to gain more space for a compact presentation of the entire database. The meanings of those numbers are as follows:

1 = sequential number replacing well names. Key wells selected for this study are indicated by an asterisk in this column,

2 = interval drilled of the Lagoa Feia Formation in each well. Wells that did not reach the basement are indicated by an asterisk following the thickness of the interval drilled,

3 = number of TOC measurements available from cuttings and cores,

4 = number of Rock-Eval pyrolysis, from which data is available,

5 = number of vitrinite reflectance measurements
available,
6 = number of drill stem tests, from which data is available,
7 = number of production tests, from which data is available,
8 = number of wireline formation tests, from which data is available.

For the cores related, the lithologic description used by Petrobras' geologists is very briefly indicated using the following codes:

DOL = Dolomites
ANH = Anhydrites
COQ = Coquinas
CLU = Calcilitites (fine-grained carbonate rocks)
SHL = Shales
SLT = Siltstones
SS = Sandstones
CGL = Conglomerates
BAS = Basalts

Numbers in brackets following the core numbers indicate the number of thin sections of that core available for this study. All the coordinates are in geographic form except for the last well in the list for which the UTM coordinates are indicated.
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