GEOLOGY OF THE CORONADO ISLANDS,
BAJA CALIFORNIA, MEXICO

A Thesis
Presented to the
Faculty of
San Diego State University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
in
Geology

by
Thomas Norman Lamb
November 1974
GEOLOGY OF THE CORONADO ISLANDS,
BAJA CALIFORNIA, MEXICO

A Thesis
Presented to the
Faculty of
San Diego State University

by
Thomas Norman Lamb
November 1974

Approved by:

[Signatures and dates]
ACKNOWLEDGMENTS

The following people and institutions offered valuable assistance at various stages of the author's Coronado Islands adventure.

The writer thanks his thesis committee members for contributing time and effort in discussing, reviewing, and revising the report. Primary thanks goes to Dr. Gordon Gastil who stimulated the writer's interest in the Coronado Islands, and suggested their exploration. Dr. Gastil and Dr. Gary Peterson offered time and effort to discuss the geological problems of the areas. Katsuc Nishikawa of the Universidad Autonoma de Baja California was instrumental in arranging permission for the author to accompany personnel of his school to the islands. The writer would like to thank the crew to the FEMEX boat Solar for transporting the groups to the islands on several occasions. Warm thanks is offered to the fishermen, Mexican Navy personnel, and the lighthouse keeper and their families of South Island for their hospitality, communication assistance, and interisland transportation. Their excellent boat handling abilities made boarding the islands and gathering of field data possible.
Financial aid from Mobil Oil Company was greatly appreciated as it permitted extended field work in the Summer months. The author is indebted to Auggie Brescia for preparing the manuscript photos and to the staff of the San Diego State University Geology Department for their assistance throughout the project. A special thanks is extended to the writer's wife, Kathy, whose patience and hard work enabled completion of the thesis.
### TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Acknowledgments</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>iii</td>
</tr>
<tr>
<td>List of Figures</td>
<td>.viii</td>
</tr>
<tr>
<td>List of Plates</td>
<td>xii</td>
</tr>
<tr>
<td>Chapter</td>
<td></td>
</tr>
<tr>
<td>1. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>General Setting</td>
<td>1</td>
</tr>
<tr>
<td>Cultural History</td>
<td>3</td>
</tr>
<tr>
<td>Geologic Studies</td>
<td>3</td>
</tr>
<tr>
<td>2. GEOLOGY OF NORTH ISLAND</td>
<td>6</td>
</tr>
<tr>
<td>General Statement</td>
<td>6</td>
</tr>
<tr>
<td>Unit N-1</td>
<td>8</td>
</tr>
<tr>
<td>Unit N-2</td>
<td>24</td>
</tr>
<tr>
<td>Unit N-3</td>
<td>25</td>
</tr>
<tr>
<td>Geologic Structure</td>
<td>26</td>
</tr>
<tr>
<td>Age of Unit N-1</td>
<td>28</td>
</tr>
<tr>
<td>3. GEOLOGY OF MIDDLE ISLAND</td>
<td>38</td>
</tr>
<tr>
<td>General Statement</td>
<td>38</td>
</tr>
<tr>
<td>Unit M-1</td>
<td>40</td>
</tr>
<tr>
<td>Unit M-2</td>
<td>47</td>
</tr>
<tr>
<td>Unit M-3</td>
<td>51</td>
</tr>
<tr>
<td>Unit M-4</td>
<td>57</td>
</tr>
<tr>
<td>Chapter</td>
<td>Page</td>
</tr>
<tr>
<td>---------</td>
<td>------</td>
</tr>
<tr>
<td>Unit M-5</td>
<td>63</td>
</tr>
<tr>
<td>Geologic Structure</td>
<td>66</td>
</tr>
<tr>
<td>Age of Middle Island Rocks</td>
<td>69</td>
</tr>
<tr>
<td>4. GEOLOGY OF SOUTH ISLAND</td>
<td>73</td>
</tr>
<tr>
<td>General Statement</td>
<td>73</td>
</tr>
<tr>
<td>Unit S-1</td>
<td>73</td>
</tr>
<tr>
<td>Unit S-2</td>
<td>79</td>
</tr>
<tr>
<td>Unit S-3</td>
<td>90</td>
</tr>
<tr>
<td>Unit S-4</td>
<td>101</td>
</tr>
<tr>
<td>Unit S-5</td>
<td>109</td>
</tr>
<tr>
<td>Unit S-6</td>
<td>118</td>
</tr>
<tr>
<td>Unit St-1 and St-2</td>
<td>130</td>
</tr>
<tr>
<td>Unit Ls</td>
<td>137</td>
</tr>
<tr>
<td>Geologic Structure</td>
<td>138</td>
</tr>
<tr>
<td>Age of South Island Rocks</td>
<td>145</td>
</tr>
<tr>
<td>5. LOCAL AND REGIONAL GEOLOGICAL HISTORY; A PERSPECTIVE</td>
<td>149</td>
</tr>
<tr>
<td>General Statement</td>
<td>149</td>
</tr>
<tr>
<td>Regional Mesozoic History</td>
<td>150</td>
</tr>
<tr>
<td>Local Mesozoic History</td>
<td>162</td>
</tr>
<tr>
<td>Regional Paleogene History</td>
<td>164</td>
</tr>
<tr>
<td>Local Paleogene History</td>
<td>166</td>
</tr>
<tr>
<td>Regional Neogene History</td>
<td>167</td>
</tr>
<tr>
<td>Local Neogene History</td>
<td>189</td>
</tr>
<tr>
<td>Chapter</td>
<td>Page</td>
</tr>
<tr>
<td>---------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>Regional Quaternary History</td>
<td>200</td>
</tr>
<tr>
<td>Local Quaternary History</td>
<td>201</td>
</tr>
<tr>
<td>REFERENCES CITED</td>
<td>205</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>218</td>
</tr>
</tbody>
</table>
### LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Coronado Islands and Adjacent Area</td>
<td>2</td>
</tr>
<tr>
<td>2.</td>
<td>North Coronado Island</td>
<td>7</td>
</tr>
<tr>
<td>3.</td>
<td>Columnar Section n-a</td>
<td>9</td>
</tr>
<tr>
<td>4.</td>
<td>Columnar Section n-b</td>
<td>12</td>
</tr>
<tr>
<td>5.</td>
<td>Unit n-1 Redbeds at Extreme South End of North Island</td>
<td>17</td>
</tr>
<tr>
<td>6.</td>
<td>Sandstone and Thin Shale Interbeds of Unit n-1</td>
<td>17</td>
</tr>
<tr>
<td>7.</td>
<td>Cross-bedded Sandstone of Unit n-1 Near Sea Level at North End of Lobster Cove, North Island</td>
<td>19</td>
</tr>
<tr>
<td>8.</td>
<td>Conglomerate Lens of Unit n-1 at Extreme South End of North Island</td>
<td>19</td>
</tr>
<tr>
<td>9.</td>
<td>Nomenclature of Late Cretaceous Sedimentary Rocks Along the West Coast of Southern California and Northwestern Baja California</td>
<td>32</td>
</tr>
<tr>
<td>10.</td>
<td>Middle Island and Middle Rock in the Middle Distance, and North Island in the Far Distance</td>
<td>39</td>
</tr>
<tr>
<td>11.</td>
<td>Conglomerate-filled Channel and Conglomeratic Sandstone of Unit m-1 on the Southeast Side of Middle Island</td>
<td>39</td>
</tr>
<tr>
<td>12.</td>
<td>Columnar Section m-a</td>
<td>41</td>
</tr>
<tr>
<td>13.</td>
<td>Columnar Section m-b</td>
<td>42</td>
</tr>
<tr>
<td>14.</td>
<td>Columnar Section m-c</td>
<td>48</td>
</tr>
<tr>
<td>15.</td>
<td>Columnar Section m-d</td>
<td>50</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>16.</td>
<td>Columnar Section m-e</td>
<td>52</td>
</tr>
<tr>
<td>17.</td>
<td>Columnar Section m-f</td>
<td>54</td>
</tr>
<tr>
<td>18.</td>
<td>Main Fault on the West Side of Middle Island Separating Unit m-1 and Unit m-2 Rocks</td>
<td>58</td>
</tr>
<tr>
<td>19.</td>
<td>Fossil Burrow in Sandstone of Unit m-3 Near the Topographic High of Middle Island</td>
<td>58</td>
</tr>
<tr>
<td>20.</td>
<td>Unit m-5 Islet East of Middle Island</td>
<td>64</td>
</tr>
<tr>
<td>21.</td>
<td>Irregular Fault Surface on the Northeast Side of the Southern Unit m-4 Fault Block, Middle Island</td>
<td>64</td>
</tr>
<tr>
<td>22.</td>
<td>South Island, Middle Island, and Middle Rock</td>
<td>74</td>
</tr>
<tr>
<td>23.</td>
<td>West Side of South Island</td>
<td>75</td>
</tr>
<tr>
<td>24.</td>
<td>Units s-1 and s-2 on Northeast Side of South Island</td>
<td>76</td>
</tr>
<tr>
<td>25.</td>
<td>Columnar Section s-a</td>
<td>77</td>
</tr>
<tr>
<td>26.</td>
<td>Flute Casts on Bottom of Unit s-2 on Northeast Side of South Island</td>
<td>86</td>
</tr>
<tr>
<td>27.</td>
<td>Sandstone, Conglomerate, and Fossil Burrows of Unit s-3 at Shoreline West of Puerto Cueva Cove</td>
<td>86</td>
</tr>
<tr>
<td>28.</td>
<td>Cross-beds of Unit s-2 South of Unit is on East Side of South Island</td>
<td>89</td>
</tr>
<tr>
<td>29.</td>
<td>Columnar Section s-b</td>
<td>92</td>
</tr>
<tr>
<td>30.</td>
<td>Slump Block in Unit s-3 Sandstone</td>
<td>99</td>
</tr>
<tr>
<td>31.</td>
<td>Sandstone Rip-up in Unit s-3 Conglomerate</td>
<td>99</td>
</tr>
<tr>
<td>32.</td>
<td>Columnar Section s-c</td>
<td>102</td>
</tr>
<tr>
<td>33.</td>
<td>Conglomerate of Lower Part of Unit s-4 East of North Lighthouse</td>
<td>104</td>
</tr>
<tr>
<td>Figure</td>
<td>Page</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>------</td>
<td></td>
</tr>
<tr>
<td>34. Blueschist Clast of 1m Diameter in Unit s-4 Near Shoreline East of North Lighthouse</td>
<td>104</td>
<td></td>
</tr>
<tr>
<td>35. Columnar Section s-d</td>
<td>111</td>
<td></td>
</tr>
<tr>
<td>36. Volcaniclastic Breccia of Unit s-5 at North End of Seal Cove</td>
<td>115</td>
<td></td>
</tr>
<tr>
<td>37. Sandstone Slump Block in Unit s-5 at North End of Seal Cove</td>
<td>115</td>
<td></td>
</tr>
<tr>
<td>38. Unit s-5, s-6 Contact at North End of Seal Cove</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>39. Bedded Siltstone and Sandstone of Unit s-6 and Underlying Volcaniclastic Breccia of Unit s-5 at North End of Seal Cove</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>40. Columnar Section s-e</td>
<td>122</td>
<td></td>
</tr>
<tr>
<td>41. Interbedded Sandstone and Shale of Unit s-6 West of Middle Peak</td>
<td>127</td>
<td></td>
</tr>
<tr>
<td>42. Unit st-1 Terrace Deposit on East Side of South Island</td>
<td>132</td>
<td></td>
</tr>
<tr>
<td>43. South End of Puerto Cueva Cove</td>
<td>132</td>
<td></td>
</tr>
<tr>
<td>44. Main Fault on West Side of Central Fault Block, West of Seal Cove</td>
<td>139</td>
<td></td>
</tr>
<tr>
<td>45. Main Fault on East Side of Central Fault Block, East of Seal Cove</td>
<td>142</td>
<td></td>
</tr>
<tr>
<td>46. Distribution of the Great Valley Sequence and Franciscan Rocks</td>
<td>155</td>
<td></td>
</tr>
<tr>
<td>47. Distribution of Franciscan-Catalina Schist Rocks Off the Southern California-Baja California Coast</td>
<td>158</td>
<td></td>
</tr>
<tr>
<td>48. Structure of the Southern California Continental Borderland</td>
<td>169</td>
<td></td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>49.</td>
<td>Distribution of San Onofre Breccia Outcrops in Southern California and</td>
<td>171</td>
</tr>
<tr>
<td></td>
<td>Northwestern Baja California</td>
<td></td>
</tr>
<tr>
<td>50.</td>
<td>Bedrock Geology of the Southern California Continental Borderland</td>
<td>175</td>
</tr>
<tr>
<td>51.</td>
<td>Middle Miocene Paleogeography of Coronado Islands and Surrounding Area</td>
<td>193</td>
</tr>
</tbody>
</table>
# LIST OF PLATES

<table>
<thead>
<tr>
<th>Plate</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. Geologic Map and Structure Section of North Island</td>
<td>Backpocket</td>
</tr>
<tr>
<td>II. Geologic Map and Structure Section of Middle Island</td>
<td>Backpocket</td>
</tr>
<tr>
<td>III. Geologic Map and Structure Section of South Island</td>
<td>Backpocket</td>
</tr>
</tbody>
</table>
Chapter 1

INTRODUCTION

General Setting

North Island, Middle Rock, Middle Island, and South Island comprise the Coronado Island group located 12km northwest of Rosarito Beach, Baja California and about 25km southwest of San Diego (Fig. 1). The Coronados are rugged desert islands that are presently devoid of fresh water except for one small spring on North Island. Biologically, the islands are typical of the southern California and Baja California coastal areas in that the predominant vegetation is Sage, Beavertail cactus, short grass, and some Crystallinium ice plant. The islands lie en echelon to one another along a north-northwest trend. Maximum interisland water depths as well as depths between the islands and the mainland do not exceed 50m. The Coronados are tilted fault blocks on a shallow shelf that extends about 20km west of the Tijuana-Rosarito Beach area (Fig. 1). The shelf is incised by Coronado Canyon 7km north of the islands and is terminated on the west by the 1100m Coronado Escarpment. West of the escarpment is the sediment-filled San Diego Trough, the easternmost...
Figure 1. Coronado Islands and Adjacent Area. Adapted from U.S. Coast and Geodetic Survey Map 1206N-16, 1967. Submarine contours in meters.
depression in a series of offshore basins and ridges that form the California Continental Borderland.

**Cultural History**

The Coronados were first christened "Los Islas Desiertas" (the Desert Islands) by Cabrillo as he sailed north in 1542. Later, in 1602, another Spanish explorer, Vizcaino, passed by the islands. A group of Carmelite friars aboard Vizcaino's ships renamed the islands "Los Cuatro Coronados" in memory of four Christian martyrs put to death in Roman times (Ellesberg, 1970). Since these explorations, the Coronado Islands have been under Spanish, and now Mexican jurisdiction. The islands are an official bird and seal sanctuary, hence, the Mexican Navy has direct jurisdiction over the islands and maintains a small garrison of military personnel on South Island. South Island is the only island presently inhabited with a fluctuating population of about twenty-five that includes military families, a lighthouse keeper and his family, and a few fishermen.

**Geologic Studies**

The subaerial geology of adjacent Baja and Alta California is relatively well known compared to the submarine geology of the local borderland. The
reader is referred to the papers of Minch (1967) and Flynn (1970) for a geologic description of the Tijuana-Rosarito Beach area directly east of the Coronados on the mainland. The work of Butcher (1951), Emergy and others (1952), Krause (1965), and Shepard and others (1969) are, to date, the most complete studies of the immediate offshore area. Woodford (1925), Hanna (1927), and Beal (1948) briefly mentioned the geology of the islands proper. The most complete description of the islands prior to the present study was reported in a doctoral dissertation by Butcher (1951) and in Emery and others (1952).

The Coronado Islands are geologically important in that they are located in a transition zone between the ridge and trough geology of the adjacent borderland and the more stable mainland to the east. The present paper attempts to describe the stratigraphy and structure of the Coronados and to analyze the island's relationship to the geology of southern California, Baja California, and the Continental Borderland.

Field work was undertaken in the Summers of 1971 and 1972 with the assistance of students from the School of Marine Sciences, Ensenada, Baja California. Section measuring was carried out by means of a jacob staff and Brunton compass. Mapping was done on air
photos from which formline maps were constructed, since no topographic maps of the islands exist.
Figure 2. North Coronado Island. View is to the southwest.
Chapter 2

GEOLOGY OF NORTH ISLAND

General Statement

North Island lies 7km south of Coronado Canyon and, being the westernmost island as well, is located only 3km east of the major break in slope of the Coronado Escarpment (Fig. 1, p. 2). The island is about 1.5km long, 0.3km wide, and 130m high at Middle Peak. The wave-eroded western side of the island has cliffs 20 to 40m high near the shore, and slanting upward to the island's crest are a series of stepped dip slopes that dip 25 to 30° west. The eastern side of the island is also quite steep except for the slope just west of Lobster Cove which is climbable (Fig. 2). North Island lithology is dominated by red sandstone. Thin beds of siltstone and shale, and a few conglomerate lenses are interstratified with the sandstone. In addition, three andesitic dikes intersect the island and a Pleistocene(?) conglomerate crops out near sea level at Lobster Cove.

Rock crops out over most of the island except near the crest and for several tens of meters down each side where a thin sandy soil covers the bedrock. Many
excellent exposures are inaccessible by normal climbing methods due to steep cliffs and/or waves breaking against the island.

Unit N-1

The west-dipping sandstone beds of unit n-1 comprise the bulk of North Island. A minimum of 205m of these redbeds are present both north and south of the two faults which are located near the center of the island (Plate 1, backpocket). Rock types are similar on either side of the faults and no correlatable marker beds crop out on either of the main north and south blocks. Although the sense and magnitude of movement on the faults is unknown, the combined thickness of strata of the north and south blocks is undoubtedly more than the measured 200+m of columnar sections n-a and n-b (Figs. 3 and 4 respectively).

Employing the classification of Folk (1968), the sandstone of unit n-1 is categorized as feldspathic litharenite to lithic arkose. By setting the percentages of quartz, feldspar and rock fragments equal to 100, average readings for seven representative thin sections are quartz 65%, feldspar 15%, and rock fragments 20%. About 95% of the quartz grains are monocrystalline with moderately sharp extinction, and the
Figure 3. Columnar Section n-a. See Plate I for traverse route.
Figure 3 continued
SANDSTONE: reddish brown, mica bearing, medium to granular grained, subangular to angular, poorly sorted, very well indurated, low porosity, some graded beds up to 50cm thick.

At the 197m level subrounded to rounded pebbles 5cm to 5cm diameter are scattered throughout the sandstone, rock types include quartzite, vein quartz, black or green metavolcanic rocks and a few granodiorite and quartz monzonite clasts.

SANDSTONE: red, mica bearing, fine to medium grained, subangular, moderately well sorted, moderately porous, massive.

SANDSTONE: reddish brown, mica bearing, medium to coarse grained, angular, poorly sorted, moderately well indurated, low porosity.

SANDSTONE: similar to that above, bedding is locally 1cm to 10cm thick and made apparent by alternating fine to medium then medium to coarse sandstone layers.

Figure 3 continued
**SANDSTONE;** similar to sandstone above.

**SILTSTONE;** red, well sorted, well indurated, low porosity, beds are 1cm to 5cm thick.

**SANDSTONE;** red, mica and shale clast bearing, fine to medium grained, subangular to angular, moderately well sorted, very well indurated, low porosity, massive except for a few beds 30cm to 3m thick.

**SILDE AND SILTSTONE;** red, thinly bedded

**SANDSTONE;** reddish brown, mica and pebble bearing, medium to coarse grained (medium grains predominate), subangular, poorly sorted, low porosity, massive, clasts are well rounded quartzite and quartz monzonite(?) pebbles.

**SANDSTONE;** reddish brown, mica and conglomerate bearing, fine to coarse grained, angular, poorly sorted, very well indurated, very low porosity, massive, clasts in conglomerate lenses are rounded to well rounded pebbles and cobbles of green, brown or black metavolcanic rock, quartz monzonite, quartzite, and pegmatite.

**SANDSTONE;** similar to sandstone above.

**SANDSTONE;** reddish brown to brown, mica and shale clast bearing, medium to coarse grained, angular, moderately sorted, very well indurated, low to moderate porosity, massive, shale clasts are 0.5cm to 2cm long and locally comprise up to 5% of the sandstone.

**SANDSTONE;** similar to that above except for numerous thin beds 1cm to 30cm thick (1cm to 10cm thick beds are most common), relatively straight bedding planes, slight difference in grain size reveals individual beds.

_Sandstone of this columnar section is feldspathic litharenite to lithic arkose. The classification scheme of Folk (1959) is used._

**Figure 4. Columnar Section n-b.** See Plate I for traverse route.
Top of section abuts a normal northeast trending fault (see Plate I.).

**UNIT N-1**

- **SANDSTONE**: brown, mica and pebble bearing, medium to coarse grained (medium grains predominate), angular, moderately well sorted, low porosity, massive, pebbles are meta-volcanic rock, granodiorite, quartz monzonite, and quartzite.

- **FAULT**: rocks above are upfaulted relative to rocks below (see Plate I. for trace of fault).

- **SANDSTONE**: red, mica bearing, well indurated.

- **SANDSTONE**: red, mica bearing, fine to medium grained (fine grains predominate), angular, moderately well sorted, well indurated, good porosity (may be due to the weathered condition of rocks exposed at the surface), massive except for a few beds 2cm to 10cm thick.

- **SILTSTONE**: red, mica bearing, well indurated, low porosity, beds 0.5cm to 2cm thick.

- Scattered red shale intraclasts are located in the 93m to 96m level, clasts are 1cm to 10cm long and tend to be oriented subparallel to general bedding trends.

- Numerous cube shaped limonite after pyrite particles are in sandstone, limonite cubes are 2mm to 0.5cm across.

- **SANDSTONE**: reddish brown, mica bearing, medium grained, angular to subangular, well sorted, very well indurated, low porosity, massive.

Figure 4 continued
remaining 5% are composite and most often have slightly undulatory extinction. Orthoclase is 5 to 20% more abundant than plagioclase as individual framework grains, however, the total plagioclase-orthoclase ratio is nearly equal due to the presence of much additional plagioclase in the form of phenocrysts in volcanic rock fragments. Rock fragment distributions in thin sections average 50% plutonic, 30% volcanic, and 20% sedimentary when these rock types are set equal to 100%. Metamorphic rock fragments are rare in unit n-l beds. Recognizable metamorphic (schist) grains account for less than 0.5% of the total rock fragment population, but some of the volcanic and sedimentary rock grains are slightly metamorphosed. The plutonic rock fragments are generally coarse-to-grit-sized, semi-rounded aggregations of feldspar and quartz crystals, whereas volcanic fragments are recognized by their fine-grained groundmass, plagioclase phenocrysts, and varying degrees of iron oxide alteration. Weathering of the volcanic fragments prevents definitive estimations of rock type in many grains, but most of the relatively unweathered grains appear to be quartz latite to dacite in composition. Most sedimentary rock fragments are probably intraclasts, since nearly all are fine-grained red sandstone and small red shale chips. Mica, the most
abundant minor constituent, is readily seen in hand specimens of unit n-1 sandstone. Thin sections have scattered grains of microcline, garnet, epidote, various opaques, chlorite, and pyroxene. Interstitial calcite is also present in small quantities. Although not characteristic of the unit n-1 redbeds as a whole, pseudomorphs of limonite after pyrite about 1mm across are locally abundant at the southern end of the island near the 87m stratigraphic level of measured section n-b (Fig. 4).

Unit n-1 sandstones are, in general, medium- to coarse-grained, poor- to moderately well-sorted, and very angular to subrounded. Fine sand grains regardless of composition tend to be very angular, whereas, medium and coarse grains are angular to subrounded. Volcanic rock fragments, particularly those of coarse sand to grit size, are subangular to subrounded. The entire sandstone section is marked by close packing of grains and a clayey iron oxide cement that results in a well-indurated rock. Low porosity and permeability has resulted from compaction and the infilling of nearly all voids with this iron oxide material. The red clayey substance penetrates all voids as well as most microfractures and pits in individual quartz and feldspar grains. Although it is difficult to estimate how much
of the red stain is actually hematite, some opaque crystals in a crystal form typical of hematite are scattered throughout this interstitial material. In thin sections the red cement makes up 2 to 10% of the total area of the slides. An abundance of volcanic rock fragments in various stages of iron oxide alteration suggests a secondary intraformational origin for the red clay.

Since clay content is typically less than 10% and most grains are angular and poorly sorted, these sandstones, according to the textural maturity scheme of Folk (1968), would be classified as immature (over 5% matrix with angular, poorly sorted grains) to submature (less than 5% terrigenous clay matrix with poorly sorted and not well-rounded grains). Assuming that the pore filling of clay developed postdepositionally, textural maturity was submature at the time of deposition.

Average thicknesses of individual sandstone beds range from 2mm to 3m, but 1 to 10cm beds prevail (Figs. 5 and 6). Close observation of many beds that appear massive from a distance reveals 1mm to 15cm beds made noticeable by slightly differing grain size or paper-thin layers of silty material. Bedding plane contacts are usually sharp especially where there are
Figure 5. Unit n-1 Redbeds at Extreme South End of North Island. View is to the northwest.

Figure 6. Sandstone and Thin Shale Interbeds of Unit n-1. View is to the north at north end of Lobster Cove.
Figure 5. Unit n-1 Redbeds at Extreme South End of North Island. View is to the northwest.
Figure 6. Sandstone and Thin Shale Interbeds of Unit n-1. View is to the north at north end of Lobster Cove.
marked grain size differences between adjacent beds, for example, shale in contact with sandstone (Fig. 6). In beds over 30cm thick lateral continuity commonly exceeds 10m, but the masking effects of weathering, soil cover, and vegetation make lateral tracing of beds difficult on many parts of the island. The majority of sandstone beds vary gradually in thickness over their exposed length and a few are distinctly lenticular (probably cross-sections of filled channels).

Sedimentary structures such as scours, load casts, cross-beds, current crests, and graded bedding are present throughout the sandstone beds. Shale rip-up clasts are common, and a few shale pieces were rolled sufficiently to form armored mudballs. Sandstone outcrops on most parts of the island exhibit some cross-beds, although cross-bedding is not apparent in a majority of the more tabular-shaped sandstone layers. Cross-bed foresets commonly range from a few centimeters to 1m in length. Near the lower part of columnar section n-a, just west of Lobster Cove, unusually large cross-beds contain individual foreset beds up to 3m long with apparent foreset dips of 8 to 14° (Fig. 7). Cross-beds are commonly associated with load casts and scouring of underlying beds, especially when beds beneath the cross-beds are fine grained. Several tens
Figure 7. Cross-bedded Sandstone of Unit n-1 Near Sea Level at North End of Lobster Cove, North Island. View is to the northwest.

Figure 8. Conglomerate Lens of Unit n-1 at Extreme South End of North Island. View is to the north.
Figure 7. Cross-bedded Sandstone of Unit n-1 Near Sea Level at North End of Lobster Cove, North Island. View is to the northwest.
Figure 8. Conglomerate Lens of Unit n-1 at Extreme South End of North Island. View is to the north.
of apparent dip readings were taken on cross-beds of North Island, but the diversity of dips and compass bearings revealed no dominant current direction. Perhaps a braided network of channels prevailed during deposition. Most sandstone layers appear to have been deposited by slow currents, but the presence of scouring, rip-up clasts, and a few graded beds suggest occasional fast currents and/or rapid movement of sediment down a slope at the time of deposition.

Blocky to lath-shaped rip-up clasts are numerous near the base of section n-a northwest of Lobster Cove. They range from 1 or 2mm to 30cm along their long axis. These rip-up clasts are reddish brown siltstone or shale typical of the finer-grained material interbedded with the sandstone of North Island. The angular, and in some cases deformed, clasts were poorly indurated at the time of disruption and were transported only a short distance before being redeposited and covered with sand. Some shale clasts, however, were rolled by currents to form well-rounded mudballs armored with small pebbles picked up during transport. The best outcrop of these red shale mudballs is located at the northwest end of Lobster Cove.

Interbedded with the sandstone, but comprising less than 5% of the total stratigraphic section, are
thin beds of red siltstone and shale ranging in thickness from a few millimeters to 15 cm. These beds are spaced randomly among the sandstone layers except for a few concentrated horizons such as just north of Cove Rock, near the 90 m level of section n-a, and at the south end of the island in the vicinity of the 50 m level of section n-b. These beds have a deeper reddish-brown color than the adjacent sandstone layers, due to a greater concentration of red muddy matrix. All samples observed in thin section were sandy, and in outcrop the siltstone and shale beds commonly grade laterally into silty sandstone. Other properties of these beds are poor sorting, low porosity and permeability, abundant mica flakes, and a high degree of induration. Bedding contacts with adjacent sandstone layers tend to be sharp, reflecting patterns of slow, quiet silt deposition followed by rapid, turbulent sand deposition. Sedimentary structures such as cross-bedding, scouring and graded bedding are similar to the aforementioned sandstone layers except for a smaller 1 mm to 10 cm length of foresets. In thin section micro-scours, cross-beds and graded beds are apparent.

Pebbles and cobbles are dispersed throughout the unit n-1 redbeds, but actual conglomerate beds are rare on North Island. The only conglomerate lenses located
by the author are at the extreme southern end of the island, but even at this locality sandstone beds dominate (Fig. 8). Conglomerate beds 1m to 3m long and 20cm to 0.5m thick are exposed on cliffs and dip slopes 30 to 60m west of the lower part of the columnar section n-b traverse (Plate I). The conglomerate clasts are well rounded and range in size from small pebbles to 20cm diameter with 3 to 10cm clasts being most common. Volcanic, metavolcanic and plutonic rocks comprise the majority of clasts in these lenses. Volcanic and metavolcanic rocks, that are green, brown or black, with plagioclase phenocrysts slightly outnumber plutonic clasts, most of which are quartz monzonite. No clasts of schist were located, and the small number of quartz rich fine-grained rocks present may be vein quartz or quartzite. In addition, a few subangular clasts of orthoclase-rich pegmatite are present in the conglomerate and conglomeratic sandstone beds.

No fossils have been found on the island, hence a definitive depositional environment determination for the unit n-1 redbeds is difficult. In many ways the cross-bedded, texturally immature rocks of North Island resemble fluvial deposits of a river flood plain or braided stream system. Employing this model, one may
assume that sedimentation in or near main stream channels included the conglomerate lenses and cross-bedded sandstone, while the deposition of shale and siltstone interbeds and tabular sand layers took place during periods of flooding. Most of the deposition must have been in the form of advancing tabular sand layers that maintained a moderately uniform thickness. Moderately fast currents were necessary to deposit the sand, but water with a slow rate of current movement would sometimes cover the area and allow suspended silt-sized particles to settle in thin layers. Anomalously fast currents, in channels more than 1m deep, periodically transported coarse sand, pebbles and cobbles to the area. Between these influxes of water and sediment, the area was subjected to subaerial oxidation indicated by the iron oxide stain throughout the entire North Island section and by the presence of armored mudballs. Such an authigenic origin for the iron oxide is plausible since many volcanic rock fragments are appreciably redder than the surrounding grains and are in various stages of decomposition from fresh to extensive red clay alteration.

Citing examples of Recent deposits in the northern Gulf of California area, Walker (1968) suggested that the oxidizing conditions of marine-fluvial
transition areas are especially conductive to the
development of redbeds where sufficient mafic minerals
are available for alteration to limonite and hematite.
The North Island redbeds may have formed in such a
marine-nonmarine transition zone.

Unit N-2

Three badly weathered, light brownish-green
dikes near the central faulted area of the island
comprise unit n-2 (Plate I). The dikes are 0.5 to 1.5m
wide, trend northeast, and dip 40 to 65° east. Although
weathering makes rock identification difficult, they
appear to be andesitic in composition. Weathered
plagioclase phenocrysts comprise 10% of the dikes.
Dike rock groundmass is about 90% plagioclase laths
0.03 to 0.1mm long, 5% opaque minerals and the remainder
is largely orthoclase and clay minerals. The two dikes
west and northwest of Lobster Cove are largely volcanic
breccia, containing angular 1.0 to 0.7m clasts of
volcanic rock and locally derived red sandstone.
Sandstone country rock accounts for approximately 20%
of the total breccia fragments, the rest are of volcanic
origin with a composition similar to the groundmass of
the dike. A common prefaulting origin is probable for
the dikes since one is cut by a fault and all have
similar groundmass compositions. The dikes are too badly weathered to be radiometrically dated, but intrusion most probably took place in the Miocene when volcanism was prevalent in the adjacent islands.

Unit N-3

Patchy erosional remnants of a Pleistocene(?) conglomerate (unit n-3) crop out near sea level at Lobster Cover (Plate I). The only outcrops located by the author are near this cove, but other outcrops may be present around the island in relatively inaccessible areas. The Lobster Cover outcrops are situated unconformably on wave-cut benches and eroded depressions cut in the red sandstone and siltstone of unit n-1. Subaerial outcrops are no more than 2 or 3m above sea level and vary in thickness from thin 1cm to 5cm coatings to masses 1.5m thick containing boulders. The conglomerate matrix, a muddy feldspathic sublitharenite, is light brown, medium-to course-grained, angular, very poorly sorted, well indurated, calcite bearing, low in porosity and permeability, and contains up to 45% silty matrix. About 60% of the conglomerate clasts are red sandstone typical of the local North Island redbeds. These clasts range from a few centimeters to 1.5m diameter with 10 to 30cm clasts being
most common. Due to the short transport distance these rocks are very angular to subangular. The remainder of the clasts are reworked and consist of subequal amounts of metavolcanic rock, vein quartz, and plutonic clasts. In contrast to the sandstone clasts these rocks are generally 3 to 10 cm in diameter, rounded to well rounded and have well-polished surfaces. The percentage of similar rocks in the redbeds of North Island is much less than in the unit n-3 conglomerate. The clasts were probably weathered out of the sandstone of unit n-1 and concentrated by wave action at sea level or in the shallow subtidal zone during a slightly higher stand of sea level in the Pleistocene.

Geologic Structure

The strata of North Island form a homoclinal structure that strikes N10°W to N25°W and dips 20 to 33° west. Bedding attitudes, even near faults, are markedly uniform. Faulting and jointing in the redbeds is dominated by a conjugate system of northwest-northeast fractures. Major faults of the island strike northeast (Plate I). In contrast to bedding attitudes, which dip west, all faults and joints observed dip east 45 to 75°.

The northernmost of the two main faults west
of Lobster Cove strikes N25°E to N30°E, dips 60°SE, and has slickensides that plunge 50°NE on the fault plane. A somewhat shallower-dipping fault is located just south of the above discussed fault. Although no slickensides were located, the sense of slip is most likely parallel to the underlying fault only a few meters away. This fault plane has a N20°E strike and dips 30°E near Lobster Cove. Relative displacement along either fault was not possible to determine because no marker beds were found. Similarly, rocks bordering two northeast trending faults at the southern end of the island reveal no clues to whether the movement was normal or reverse, but slickensides near the topographic high of the faults plunge 65° on the fault planes in a due south compass direction, suggesting nearly dip slip movement at least in the later stages of motion. The northernmost of these southern faults strikes N40°E and dips 75°E. The secondary fault to the south dips 80°E and strikes N35°E. Even though direct evidence is lacking, a third fault in the area is inferred in the passage immediately north of South Rock because of the differentially eroded linear channel at this locality. Wave erosion along this relatively weak zone has left only a bridge of brecciated rock separating the main part of the island from South Rock.
Northwest and northeast trends also prevail in the joints of North Island. Strikes of N85°E to N75°W are present, but most joints trends N20°E to N45°E and N10°W to N60°W in conjugate systems. Nearly all dips of joint planes, are between 28 and 70°E. The majority of joints in the accessible areas were 1 to 3m apart. Jointing in many parts of the island is concealed by the resistant nature of the sandstone and by soil cover.

**Age of Unit N-1**

A paleontologic age determination for the North Island redbeds is not possible since several samples of shale and siltstone proved to be barren of microfossils. Likewise, the lack of submarine stratigraphic and structural data for the Coronado Islands area precludes any direct correlation with beds of known age on the mainland or nearby offshore areas. The author has compared the lithology of North Island to mainland rocks and construed a tentative age. As will be developed in the following discussion, the author believes the redbeds of North Island to be westward equivalents of the Late Cretaceous, nonmarine Lusardi Formation of the San Diego region.

The provenance of unit n-1 was at least
partially plutonic as indicated by the quartz monzonite and pegmatite clasts in conglomerate, and the appreciable microcline and plutonic rock fragments in the sandstone. The most likely source for this plutonic detritus is the Peninsular Range batholith, which crops out as close as 40km to the east of North Island. The average composition of the batholith is more basic than the quartz monzonite clasts found on North Island. However, being 40+km from the batholith, the more resistant (acidic) clasts may have been concentrated by the forces of weathering and transport abrasion.

The oldest known occurrences of Peninsular Range plutonic rocks in sedimentary beds are in Upper Cretaceous conglomerate and sandstone deposits along the west side of the batholith. Widely scattered occurrences of such rocks include the Trabuco Formation 16km east of Santa Ana (Popenoe, 1941); limited conglomerate outcrops east of Carlsbad (Peterson and Nordstrom, 1970); the Lusardi Formation near Rancho Santa Fe (Nordstrom, 1970) and an eastern equivalent near Poway (Peterson, 1971); subsurface conglomerate in the western and southwestern San Diego area (Hertlein and Grant, 1939); the Redonda Formation east of Tijuana (Flynn, 1970); and the La Bocana Roja Formation near El Rozario 350km south of the international border.
(Kilmer, 1965). The Trabuco Formation is described by Popenoe (1941) as a red boulder conglomerate deposited on metamorphic and plutonic basement rocks. Upper Cretaceous marine beds overlie the Trabuco (Popenoe, 1941). The conglomerate beds 5km east of Carlsbad are poorly exposed, badly weathered, and are only locally reddish in color (Peterson and Nordstrom, 1970). As with the Trabuco Formation, marine deposits of Late Cretaceous age (Bandy, 1951; Popenoe and others, 1960; Holden, 1964) directly overlie these conglomerate beds. Ten kilometers south of Carlsbad the Lusardi Formation, an Early to Late Cretaceous, poorly sorted cobble and boulder conglomerate, crops out in isolated patches within a 7km radius of Rancho Santa Fe (Nordstrom, 1970). Fifteen kilometers east and southeast of Rancho Santa Fe, near Poway, an equivalent of the Lusardi Formation crops out as a remnant of fluvial channel deposits (Peterson, 1971). Although surface outcrops of the Lusardi are limited to the area around Rancho Santa Fe and Poway, a possible correlation with the subsurface redbeds in the San Diego area is suggested by Peterson and Nordstrom (1970). These Lusardi equivalents lie below known Upper Cretaceous beds in three nonproducing oil wells. The closest of the three wells to actual Lusardi outcrops is the Borderland
Exploration Company's Point Lorna #1 well located near the northeast end of the Point Loma Peninsula.

Hertlein and Grant (1939, p. 74-75) report that this well met a hard reddish-brown sandstone at 2,771 ft. (842m), and a hard red conglomerate with pebbles up to 3 in. (7.5cm) diameter at 3,670 ft. (1,116m), yielding a total redbed sequence over 270m thick. The Egger #1 well near the southern end of San Diego Bay in the Otay River floodplain encountered similar redbeds. Using lithologic, induction electrical and sonic logs, Elliott (1964) described the rock sequence in this well from 4,920 ft. (1,496m) to 5,250 ft. (1,596m) as a conglomerate redbed member of the Rosario Formation. The name Rosario has since been elevated to a group and subdivided into the Lusardi, Point Loma and Cabrillo Formations (Kennedy and Moore, 1971)(Fig. 9). Two and a half kilometers southeast of the Egger well in the Tia Juana River floodplain, the Holderness #1 well struck redbeds below known Cretaceous strata at 5,203 ft. (1,586m). In Elliott (1964) E. Dean Milow interpreted the 5,203 ft. (1,586m) to 5,529 ft. (1,686m) section of the Holderness well as a redbed member of the Rosario Formation. Direct correlation of the redbeds between respective wells is tenuous, but a similar lithologic sequence occurs with increasing depth in all three wells,
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Williams Fm.</td>
<td>Rosario Fm. (near Carlsbad only)</td>
<td>Cabrillo Fm.*</td>
<td>Point Loma Fm.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>La Brea Fm.</td>
<td>Lusardi Fm.</td>
<td>Lusardi Fm.</td>
<td>Redonda Fm.</td>
<td>Lusardi Fm.</td>
<td>La Socana Roja Fm.</td>
</tr>
</tbody>
</table>

* Point Loma and Cabrillo Formations are equivalents of Rosario Formation of earlier authors.

Figure 9. Nomenclature of Late Cretaceous Sedimentary Rocks Along the West Coast of Southern California and Northwestern Baja California.
e.g., redbed lithology below known Upper Cretaceous sediments followed by basement rock from 15 to 150m below the red sandstone and/or conglomerate layers. Another coarse clastic deposit in the region is the Redonda Formation, a conglomerate and breccia unit that overlies basement rock 20km southeast of Tijuana (Flynn, 1970). The Redonda Formation is assigned a Late Cretaceous age by Flynn on the basis of the proximity to overlying late Cretaceous Rosario Formation rocks and the presence in the Redonda of locally derived plutonic clasts. Similar redbeds in the El Rosario area 350km south of the International Border were termed La Bocana Roja Formation by Kilmer (1965). According to Kilmer these continental beds are maroon and pink claystone, sandstone, and conglomerate 90 to 1,200m thick that underlie Late Cretaceous (Late Campanian) marine rocks.

The redbeds in the Santa Ana Mountains (Trabuco Formation) and near El Rosario (La Bocana Roca Formation) are perhaps too far away to be of significance in comparing local Cretaceous redbed sedimentation, but the outcrops and subsurface occurrences of continental beds in the Tijuana, San Diego, Poway, and Rancho Santa Fe areas is indicative of post-batholithic nonmarine deposition on a regional scale along the west side of the northern Peninsular Ranges batholith. Of the local
Lusardi-type rocks, Peterson (1971, p. 233) stated, "The Lusardi Formation is apparently of much greater extent than was previously recognized (Nordstrom, 1970). It would not be surprising to find still further outcrops now that it has been recognized as a separate, distinct, and widespread stratigraphic unit. Evidently, it was deposited over a large part of the San Diego region following the emplacement of the southern California batholith and the subsequent uplift necessary to expose those deep-seated rocks. During Late Cretaceous time the San Diego region was probably topographically very rugged and undergoing rapid erosion. The high-relief topography was partially filled with debris derived from the batholithic and prebatholithic rocks and representing a very high energy depositional environment. Very coarse stream deposits, alluvial fan deposits, and mudflow deposits were spread over the area to unknown but highly variable depths. In the western part of the San Diego area, the marine Point Loma and Cabrillo Formations were deposited over the Lusardi conglomerates.

To correlate the redbeds of North Island to the Lusardi Formation on the basis of nonmarine appearance alone would be tenuous at best. However, a comparison of clast types in conglomerate beds of the two deposits
strengthens the suggested correlation. A unique property of the Lusardi Formation and other conglomerates in the Rosario Group is their lack of Poway-type clasts (Peterson and Nordstrom, 1970). Clasts of the Poway Suite (Peterson and others, 1968) are typically very resistant purple to red, weakly metamorphosed dacitic to rhyolitic volcanic and pyroclastic rocks. Comprehensive studies of these clasts are found in the works of Bellemin and Merriam (1958), Delisle and others (1965), and Woodford and others (1968). Poway clasts were transported by rivers to southwestern San Diego County during Eocene time from source areas east of the Peninsular Ranges (Minch, 1972). Poway Suite rocks are of course abundant in the Poway Group deposits, but they are also present as reworked clasts in virtually all post-Eocene formations in the San Diego area (Peterson and Nordstrom, 1970). Miocene sediments of South and Middle Coronado Islands also contain reworked clasts typical of the Poway Suite. However, in accord with Cretaceous sediments of the San Diego area the redbeds of North Island are devoid of Poway-type rocks, but do contain abundant rocks and minerals characteristic of the Peninsular Range batholithic and metamorphic terrain. Based on these clast associations and the apparent nonmarine character of unit n-1, the author
proposes that the redbeds on North Island are seaward equivalents of the Lusardi Formation.

Even though the Lusardi deposits on the present-day mainland are highly conglomeratic, indicating high relief in the area (Peterson, 1971), much lower energy conditions could have prevailed to the west in the Coronado Islands area, resulting in predominantly sandstone deposition. The thin bedded sandstone and shale on North Island may reflect more subdued topography and depositional energy of a marine-nonmarine transition zone.

The Egger #1 well and the Holderness #1 well, both of which are located about 15km to the northeast, mark the closest occurrence of known Cretaceous redbeds to North Island. These two wells encountered redbeds at depths in excess of 1,490m, and the Point Loma #1 well 20km to the north struck redbeds at 842m. Although these mainland redbeds are located at depth, structural trends of the San Diego-Tijuana area make a western subaerial outcrop of Cretaceous beds plausible. For example, the Point Loma Peninsula (Fig. 1, p. 2) and Mount Soledad in western San Diego are two cases of uplift on the west side of faults that has resulted in the exposure of Cretaceous Cabrillo and Point Loma Formation rocks. Faulting and folding of a similar
nature could easily have exposed Cretaceous rocks in the Coronados area. Mount Soledad, the Point Loma Peninsula, and the Coronado Islands are roughly aligned on a north-south axis and may represent portions of a north-south deformational belt.
Chapter 3

GEOLOGY OF MIDDLE ISLAND

General Statement

Middle Island and Middle Rock are located about 1km west of South Island (Fig. 10). Middle Rock, located 250m northwest of Middle Island, is about 150m long and 25m at its maximum height. Middle Island is approximately 300m long and is 90m above sea level near the center of the island. A small islet to the east of Middle Island is separated from the main island by a shallow, narrow water passage except during extreme low tide. The steep flanks of Middle Island culminate in a narrow, peaked ridge that extends nearly the whole length of the island.

Middle Island is the smallest yet structurally most complex of the three main Coronado Islands. In this report its twelve major structural fault blocks have been assigned to five mappable units on the basis of lithologic similarities. A tentative middle Miocene age, based on local and regional rock similarities, is assigned to the rocks of Middle Island and Middle Rock.
Figure 10. Middle Island and Middle Rock in the Middle Distance, and North Island in the Far Distance. View is to the northwest from South Island.

Figure 11. Conglomerate-filled Channel and Conglomeratic Sandstone of Unit m-1 on the Southeast Side of Middle Island. View is to the southwest.
Figure 10. Middle Island and Middle Rock in the Middle Distance, and North Island in the Far Distance. View is to the northwest from South Island.
Figure 11. Conglomerate-filled Channel and Conglomeratic Sandstone of Unit m-1 on the Southeast Side of Middle Island. View is to the southwest.
Unit M-1

Reddish-brown sandstone and conglomerate of unit M-1 comprises the whole of Middle Rock, plus the western margin and the northern and southern tips of Middle Island (Plate II, backpocket). The Middle Island unit M-1 section is about 40m thick (Figs. 12 and 13), and although Middle Rock was not boarded due to wave conditions, the total section there is probably in excess of 60m. These conglomeratic red beds are the most resistant rocks of Middle Island. Their occurrence on the west (windward) side of the island has successfully sheltered the other less well-indurated sediments from wave erosion, and may be responsible for the very existence of Middle Island today. West Cove is a differentially eroded inlet where wave action has breached the redbed barrier along a fault and begun eroding less resistant sandstone beds of unit M-2 (Plate II).

The unit M-1 beds are, by volume, roughly half conglomerate lenses and half red sandstone and conglomeratic sandstone (Fig. 11). The three major grain types average 40% quartz, 20% feldspar, and 40% rock fragments when these constituents are arbitrarily summed to equal 100%. Quartz and feldspar grains tend to be quite angular, but the less resistant rock fragments are
CONGLOMERATE; similar to conglomerate below, one sandstone clast has 3 cm long and 1 cm diameter fossil worm tube.

SANDSTONE; similar to sandstone below, upper part of bed is scoured.

CONGLOMERATE AND CONGLOMERATIC SANDSTONE: similar to rocks below only in beds 2 cm to 30 cm thick, some filled channels at contact with sandstone below.

SANDSTONE: reddish brown, calcite, pebble, and cobble bearing, medium to coarse grained, angular, moderately well sorted, well indurated.

CONGLOMERATE: massive with a few sandstone lenses. Matrix and sandstone lenses: reddish gray, calcite bearing, fine to granular grained, angular, very poorly sorted, very well indurated, massive. Clasts: pebble size to 100 cm diameter, 3 cm to 10 cm diameter most common, pebbles are subangular to subrounded, clasts over 3 cm diameter are subrounded to rounded, approximate percentages of rock types are: volcanic and metavolcanic 30%, quartzite, quartz and quartz-rich schist 15%, sandstone 25%, plagioclase 2%, and mica schist, chlorite schist and blueschist 15%.

Sandstone and sandy conglomerate matrix of this section are feldspathic volcanic arenites. The classification scheme of Folk (1968) is used.

Figure 12. Columnar Section m-a. See Plate II for traverse route.
Figure 13. Columnar Section m-3. See Plate II for traverse route.
angular to subangular. Accessory minerals are biotite, hornblende, pyroxene, epidote, glauconite, and garnet. Calcite is present as interstitial material, and a few quartz grains are partially replaced by grainy calcite. The rock fragment population in the sandstone beds and conglomerate matrix is about 80% volcanic, 15% metamorphic, and 5% plutonic and sedimentary. Most of the volcanic grains are altered fine-grained fragments or devitrified glass. In general, the volcanic fragments are composed of very small crystals of plagioclase and chlorite, but one-third of the grains also contain larger plagioclase phenocrysts. Virtually all volcanic grains are altered to varying degrees with chlorite being the main replacement mineral. Metamorphic fragments are mostly quartz-rich schists containing banded, subparallel and crenulated mafic minerals. Chlorite, whether original or replacement, is also present in many metamorphic grains. Rock fragments are commonly indented by neighboring quartz and feldspar grains indicating post-depositional compaction. Unit m-1 rocks as a whole are very well-indurated due to the presence of clayey red iron oxide cement that comprises 2 to 10% of the unit, and by interstitial calcite spar which makes up 1 to 3% of the rock. The ferric iron stain is homogeneously dispersed in the clayey cement.
and has penetrated even the smallest fractures and indentations of individual sand grains. It is likely that iron was released as volcanic rock fragments decomposed. In fact, many volcanic grains are themselves badly decomposed and deep red in color. The void-filling calcite may also be a residual mineral left from the alteration of mafic minerals in volcanic rock fragments.

Clasts in the conglomerate range in size from small pebbles to boulders 0.5m in diameter, though rocks in the 3 to 10cm range comprise most of the clast population. Visual field estimates of clast rock type indicate 50 to 80% rhyolite, dacite, andesite, basalt, and slightly metamorphosed equivalents of these volcanics, 10 to 30% quartzite, vein quartz or quartz-rich amphibole and chlorite schist, 2 to 10% sandstone and shale, and less than 2% plutonic clasts of quartz monzonite to granodiorite composition. About half of these plutonic clasts are slightly epidotized. There are few clasts of chlorite-plagioclase schist and blue schist typical of Catalina Schist rocks as described by Woodford (1924). The chlorite and amphibole schist clasts may also be of Catalina Schist origin. The majority of clasts in unit m-1 are of the Poway and Peninsular Ranges Suites.
Roundness of the conglomerate clasts is related to rock type and the extent of reworking, following a pattern of subangular to subrounded for the moderately resistant sandstone, shale and low grade metamorphic rocks, and rounded to well rounded for the very resistant volcanic, metavolcanic and plutonic clasts. These well-rounded resistant clasts were reworked from Cretaceous and Early Tertiary deposits.

Taken as a whole, the respective conglomerate and sandstone deposits of Middle Island and Middle Rock are randomly interbedded and each make up about one-half of the total exposed redbed sequence. The sandstone beds vary from a few centimeters thick to massive layers over 1m thick. Some of the thicker beds are laterally continuous for up to 50m, but more are highly lenticular or are terminated laterally in outcrop by conglomerate lenses. The few beds of fine-grained sandstone present in unit m-1 are 1cm to 10cm thick and discontinous in outcrop.

Conglomerate outcrops are commonly in the form of lenses 2 to 5m long or filled channels ranging from 1 to 5m wide and 0.5 to 1m deep (Fig. 11). Channel orientations are difficult to determine because of the two-dimensional perspective of most exposures, however, a strong north-south component is evident in several
small channels less than 1m across at the southern tip of the island. Cross-bedding, load casts, and scour channels are widespread in unit m-1 sandstone beds, but no conclusive evidence of preferred current or slope directions is apparent.

The lenticular shape of beds and coarse texture grains unit m-1 redbeds indicate moderately high energy conditions at the time of deposition. It is evident from cross-bedding, scouring, and the well-washed nature of the sandstone beds that current action played a major part in sediment transport, though a moderately steep slope may have been present to facilitate movement of the larger conglomerate clasts. A subaerial origin for these rocks seems likely based on their red color, and lenticular bedding. Also, the red stain in these rocks probably developed from periodic exposure to the atmosphere during periods of nondeposition. The presence of glauconite (a mineral produced in a marine environment) does not necessarily indicate a marine depositional environment in the case of unit m-1. These grains are sparsely distributed in the unit m-1 sandstone and are detectable only in thin sections, hence, it is likely that these grains were derived from earlier marine beds and subsequently deposited in a nonmarine environment.
Unit M-2

Rocks of unit m-2 are directly adjacent to unit m-1 in the middle and northern parts of the island (Plate II). Unit m-2 consists of over 60m of fractured and folded marine sandstone, siltstone, and shale. Units m-1 and m-2 are separated by normal, east-dipping faults, hence, unit m-2 rocks are stratigraphically higher than the unit m-1 redbeds (Fig. 18, p. 58). Just east of West Cove at the traverse route of columnar section m-c (Plate II), an exposed cliff face contains 40m of interbedded brown to gray siltstone, sandstone and shale of unit m-2. Only the lower 5m is accurately described due to limited accessibility of the outcrop. The sandstone of these lower few meters of columnar section m-c (Fig. 14) is gray, mica-bearing, pebble-bearing, and calcite-bearing, medium-grained, moderately well-sorted, well-indurated, and low in porosity. Bedding is in layers 0.5 to 2m thick that decrease in average thickness to about 20cm near the top of the section. Sandstone comprises about 70% of the section's lower 10m and 90% of the outcrop from the 20m level upward. Gray to brown, 3 to 20cm thick shale beds are intermittently spaced throughout the cliff and make up 20% of the exposed outcrop near the bottom and 5 to 10% near the top of section m-c.
Near crest of island, rocks are similar to those below except for thinner 30cm to 50cm thick pebbly sandstone beds.

In the 25m to 30m part of the section sandstone in beds 20cm to 1m thick make up 65% of the rocks, thin bedded siltstone and shale comprise 15% of the section.

**SANDSTONE, SILTSTONE AND SHALE, (interbedded); brown to grayish brown, from 15m to 25m level sandstone is brown, pebble bearing, and crops out in 30cm to 50cm thick beds, from 15m to 25m level bedded siltstone and shale account for about 35% of the section.**

Lower 10m of section is about 20% shale. Inaccessible cliff precludes detailed description of rocks above.

**SANDSTONE; gray, mica and calcite bearing, medium grained, moderately well sorted, well indurated, low porosity, massive.**

**SANDSTONE AND SILTSTONE, (interbedded); grayish brown, mica and calcite bearing, fine to medium grained, moderately to well sorted, moderately well indurated, low porosity.**

Sandstone of this section is feldspathic volcanic-arenite. The classification scheme of Folk (1968) is used.

Figure 14. Columnar Section m-c. See Plate II for traverse route.
Lateral tracing of these unit m-2 beds northward is hindered by soil cover, vegetation, inaccessibility, and variable bedding attitudes, but the strata of measured section m-d (Fig. 15) appear to be part of the same fault block and may be, in part, a lateral equivalent of unit m-2 rocks in columnar section m-c. Section m-d is 75m thick and contains 90% light-brown sandstone beds 2 to 30cm thick. The other 10% is made up of thin sandy siltstone beds. The sandstone is calcite and mica-bearing, fine- to medium-grained, moderately well-sorted, and well-indurated. Recognized accessory minerals include biotite, glauconite, epidote, and microcline. In thin section, typical ratios of the three major constituents, quartz, feldspar and rock fragments are quartz 30%, feldspar 20%, and rock fragments 50%, hence, these sandstones are feldspathic volcanic arenites. Chips of fossil wood 1mm to 2cm long are locally abundant in unit m-2 rocks at the 55 to 60m level of section m-d just north of the highest point on the island. The marine origin of the sediments in this particular fault block is revealed by a few fossil burrow casts and a 20cm block of sandstone found near the crest of the island that contains numerous disarticulated pelecypod valves. These fossils are discussed later in this chapter under the
A columnar section is shown with various units and stratigraphic layers. The section notes the presence of sandstone and siltstone, with descriptions of their characteristics, such as color, grain size, and internal features. Fossils and other sedimentary features are also noted, including paleocurrent directions. The section also includes a conjecture about the nature of the sandstone's origin and its possible volcanic or volcanic-arenite composition.

The text includes the following layers:
- **SANDBEACH**: Grayish brown, mica and fossil wood chip bearing, fine grained, well sorted, moderately well indurated, beds 1cm to 50cm thick, 1cm to 5cm beds are most common.
- **At this level a well indurated brown sandstone block of "float" material containing fossil pelecypods and gastropods was present on the slope surface. See text for analysis of these fossils.**
- **SANDBEACH AND SILTSTONE, (interbedded):** Sandstone is light brown, calcite and mica bearing, fine to medium grained, poor to moderately sorted, moderately well indurated, low porosity, siltstone is also light brown, moderately well indurated, and is locally fissile (shale). Both sandstone and siltstone occur in beds 10cm to 50cm thick.
- **SANDBEACH; similar to sandstone below, pebble bearing, average thickness of bedding is 2cm to 6cm.**
- **FAULT; relative displacement not apparent. Rock type on either side of fault is similar sandstone.**
- **SANDBEACH; similar to that below, exposure masked by soil cover.**
- **SANDY SILTSTONE; greenish brown, mica and fossil wood chip bearing, silt to fine sand in grain size, well sorted, well indurated, low porosity, locally fissile (shale).**
- **SANDBEACH; light brown, mica and calcite bearing, medium grained, moderately well to well sorted, very well indurated, medium porosity, beds 5cm to 70cm thick, 10cm to 15cm beds most abundant.**

Figure 15. Columnar Section m-d. See Plate II for traverse route.
Age of Middle Island Rocks.

Unit M-3

Rocks of unit m-3 comprise a large fault block on the east side of the island and a smaller fault slice west of the islet on the east side of Middle Island (Plate II). Approximately 95m of strata, represented by columnar sections m-e and m-f (Figs. 16 and 17 respectively), are present in these two fault blocks. Due to their similar rock type, sections m-e and m-f may be, in part, lateral equivalents of each other, but no direct correlation is evident in the field. Because several minor faults cut through unit m-3 and landslide debris covers portions of the island's surface in this area, not all rock layers are exposed in continuous sections up the side of the island.

The lower 15m of section m-e near the eastern shoreline, though largely concealed by vegetation and rockslide debris, is gray, fine- to medium-grained, calcite-cemented sandstone. The 1 to 3m wide areas where the bedrock is exposed show very little evidence of bedding. The conglomeratic sandstone from the 15m to the 22m level is gray-brown in color, fine- to coarse-grained, well-indurated, massive like the underlying sandstone, and contains clasts of resistant volcanic,
SANDSTONE: brown, mica bearing, medium grained, angular, moderately well sorted, well indurated, medium porosity.

SILTY SANDSTONE: brown, mica and wood chip bearing, fine grained with silt, well sorted, well indurated, medium porosity, bedding is 30cm to 50cm thick.

FAULT: rocks above are upfaulted relative to the rocks below.

SANDSTONE: light brown, mica, calcite, and cobble bearing, fine to medium grained, sub-angular, moderately well to well sorted, well indurated, bedded 30cm to massive. About 1% of cobbles are schist of Franciscan origin.

CONGLOMERATE: similar to lenses below.

SANDSTONE: brown, calcite, pebble and cobble bearing, medium to coarse grained, moderately sorted, moderately to well indurated, medium porosity, moderate permeability, mostly massive with a few cross beds.

SANDSTONE: brown, mica and calcite bearing, fine to granular grained, very poorly sorted, well indurated, moderate porosity, lenticular shaped beds 15cm to 1m thick and 1m to 10m long in outcrop, interbedded conglomerate lenses with matrix similar to this sandstone, cobbles are pebble sized to 30cm diameter, some chlorite schist and blue schist of Franciscan origin.

SANDSTONE: reddish brown, calcite bearing, fine to granular grained, angular to sub-angular, very poorly to moderately well sorted, low porosity, beds 10cm to 50cm thick, conglomerate interbeds are about 30% clasts and 70% matrix, 2m to 10m long in outcrop, clasts are small pebbles to cobbles 15cm diameter, some Franciscan chlorite schist and mica schist clasts.

SANDSTONE: grayish brown, calcite, pebble and cobble bearing, fine to granular grained, subangular, very poorly sorted, very well indurated, moderately porous, some graded beds 3cm to 30cm thick, other lenticular beds 30cm to 50cm thick and 15m maximum length in outcrop.

SANDSTONE: gray, mica and cobble bearing, fine to medium grained, subangular, moderately well sorted, very well indurated, low porosity massively bedded except near conglomerates above.

SANDSTONE: similar to that above but contains no apparent cobbles, beds are 5cm to 15cm thick.

CONGLOMERATIC SANDSTONE: grayish brown, mica, calcite, pebble, cobbles, and red shale intraclast bearing, fine to coarse grained, angular, very poorly sorted, very well indurated, low porosity, massive, some conglomerate lenses 3m to 5m in outcrop length, red shale clasts are blocky in shape and 2cm to 3cm across.

SANDSTONE: gray, calcite and "ironstone" concretion bearing, fine to medium grained, subangular, moderately well sorted, very well indurated, low porosity, massive, landslide rubble obscures lower few meters of section.

Sandstone and sandy conglomerate matrix of this section are feldspathic volcanic arenites. The classification scheme of Folk (1975) is used.

Figure 16. Columnar Section m-s. See Plate II for traverse route.
CONglomerate and Sandstone, (interbedded); Sandstone; light brown, calcite and mica bearing, medium to coarse grained, well indurated, beds 2cm to 15cm. Conglomerate; beds 30cm to 1m thick, lenticular in outcrop, some Franciscan blueschist clasts.

Fault; beds above are upfaulted relative to the beds below.

Sandstone; similar to that below.

Figure 16 continued
CONGLOMERATE AND SANDSTONE; grayish brown, sandstone and conglomerate (matrix) are coarse grained, angular, poorly sorted, well indurated and massive.

SANDSTONE; brown, pebble, cobble, quartz bleb and fossil wood chip bearing, fine to medium grained, well sorted, well indurated, medium porosity, tubular shaped fossil animal burrows 2cm diameter and about 30cm long.

CONGLOMERATE AND SANDSTONE; bedding planes of most conglomerate layers are irregular and possibly are filled channels, width of channels is up to 3m.

SANDSTONE AND SILTSTONE, (interbedded); beds are 0.5cm to 1.5m thick.

CONGLOMERATE; irregular contact with surrounding beds, lenticular and 10m long in outcrop.

SANDSTONE LENSES; greenish brown, coarse to granular grained, angular to subangular, very poorly sorted, moderately indurated, low porosity.

SANDSTONE; gray, calcite and wood chip bearing, medium to coarse grained, moderately sorted, very well indurated, medium porosity, some cross bedding on a scale less than 15cm.

SILLSTONE LENSES; gray, 30cm to 50cm thick.

COBBLES IN SANDSTONE; cobbles of quartzite, quartz, basalt, rhyolite, andesite, quartz monzonite.

SANDSTONE AND SILTSTONE; (interbedded); similar in physical make up to sandstone and siltstone below, some small scale cross bedding.

SANDSTONE CLUMP BLOCK; brown, 1.5m diameter, blocky shape, tilted relative to surrounding bedding, apparently slid into place on a slope.

SANDSTONE AND SILTSTONE; similar to sandstone and sandy siltstone below only interbedded and lenticular.

SANDY SILTSTONE; dark gray, calcite bearing, well sorted, well indurated, very low porosity, some irregular lenticular sandstone stringers 30cm to 5cm long in outcrop.

SANDSTONE; gray, calcite bearing, medium grained, angular, moderately well sorted, very well indurated, low porosity, massive, some dark gray siltstone lenses 2cm to 15cm thick.

Sandstone and sandy conglomerate matrix of this section are feldspathic volcanic -arenites. The classification scheme of Folk (1968) is used.

Figure 17. Columnar Section m-f. See Plate II for traverse route.
metamorphic, and plutonic rock. Angular and deformed red shale clasts are also numerous in the sandy conglomerate matrix. The red color and fine-grained nature of these chunks are anomalous in comparison to the unit as a whole. Red silty sediment that had not been fully lithified was apparently ripped up from a nearby subaerial source, and transported by currents to the immediate area. A red shale slump block 1m thick and 10m long that most likely originated in the same area as the red shale chips crops out at the 31m stratigraphic level of section m-e. The block is uniform in attitude internally, but is at an angle to the prevailing local strike and dip of unit m-3. A moderately steep slope must have been present between the site of deposition and the source area to facilitate transport of this block. Conglomeratic sandstone and conglomerate lenses dominate the upper 60m of section m-e. Sandstone beds are medium to coarse in grain size, brown, and form beds 15 to 30cm thick. Conglomerate layers are highly lenticular, contain a few Catalina Schist-type blueschist clasts, and are laterally continuous for only 2 to 10m in outcrop.

The unit m-3 fault block west of the islet is represented by columnar section m-f (Fig. 17). Section m-f is 80m thick and consists mainly of sandstone and
interbedded siltstone with some conglomerate in the upper 20m. Sandstone beds are gray, calcite-bearing, mica-bearing, fine- to coarse-grained, moderately well- to well-sorted, well-indurated, and tightly packed. Siltstone interbeds are gray- to dark-gray, well- indurated, and extremely low in porosity. Sandstone beds in the lower 60m of the section are lenticular, especially in strata where siltstone is the predominate rock type. Thicknesses of the sandstone layers vary from a few centimeters to over 30cm. Individual 2 to 10cm lenses are less than 1m long, and thicker beds are up to 10m long. Conversely, siltstone layers are generally less than 15cm thick with greater lateral uniformity in thickness, reflecting quiet depositional conditions. Pebbles of quartzite, vein quartz, basalt, and plutonic rocks are interspersed among all rocks of section m-f, but only in the upper portions of the section does conglomerate make up a major part of the strata. One distinctive conglomerate lens 10m in outcrop length occupies a scoured channel in underlying sandstone at the 40m level of the section. Beginning at the 60m horizon, conglomerate predominates for 7.5m up section where it is terminated by a fault. West of the fault is 10m of brown, pebbly, fine- to medium-grained sandstone containing scattered wood chips,
quartz blebs that may have replaced organic material, and a conglomerate lens that forms part of the crest of the island.

Attestin g to a marine depositional environment, several curved, sand-filled burrows 3cm diameter and up to 30cm long are located in disattached sandstone blocks on the east side of the island's crest (Fig. 19). Before sliding a few meters down the east slope of the island these slump blocks were lateral equivalents of the upper 10m of section m-f.

Cross-bedding in many sandstone beds indicates that current action was important in submarine sand transport, though other sandy layers show graded bedding. The large red shale slump block and the poorly sorted conglomeratic material of this unit were probably carried sown a slope by gravity.

Unit M-4

Two fault blocks in the northeast and southeast parts of the island respectively, containing beds of sandstone, siltstone, shale, and conglomerate, are designated unit m-4 (Plate II). Direct correlation between the two fault blocks is not possible, and they may represent different stratigraphic horizons. However, the grouping of these rocks into one unit is based on
Figure 18. Main Fault on the West Side of Middle Island Separating Unit m-1 (to left of fault) and Unit m-2 Rocks. View is to the northwest.

Figure 19. Fossil Burrow in Sandstone of Unit m-3 Near the Topographic High of Middle Island.
Figure 18. Main Fault on the West Side of Middle Island Separating Unit m-1 (to left of fault) and Unit m-2 Rocks. View is to the northwest.
Figure 19. Fossil Burrow in Sandstone of Unit m-3 Near the Topographic High of Middle Island.
the relative abundance of Catalina Schist conglomerate clasts which appear in each of these fault blocks.

The southern exposure of unit m-4 is a topographically high fault block comprising over 50m of marine sedimentary rock. Bedding attitudes in this structurally complex block are variable, but a general strike of north to N10°E, and dips of 15 to 20°W are commonest. Near the shoreline, where a northwest trending fault forms the northern limit of this block, a section of greenish-brown to gray sandstone and conglomerate 18m thick crops out on a cliff. The lower 8m of these rocks is 70% conglomerate lenses and 30% sandstone layers. At this outcrop conglomerate clasts include rhyolite, basalt, various metavolcanic rocks, quartzite, vein quartz, sandstone and plutonic rocks, as well as plagioclase-amphibole schist, chlorite schist, mica schist, and blueschist. The latter three rock types are assumed to be of Catalina Schist origin. Plutonic rocks, which make up less than 5% of the clast population, are mostly quartz monzonite and granodiorite. Nearly half of all observed plutonic clasts contain a green mineral, possibly epidote. Clast sizes range from small pebbles to boulders 0.5m in diameter, but clasts 3 to 6cm in diameter predominate. Plutonic, volcanic and quartz-rich rocks are generally rounded to
well rounded, whereas, schist and sandstone clasts are subrounded to subangular. The upper 10 to 12m of exposed section at this locality shows a gradual increase in sandstone layers at the expense of conglomerate.

Near the shoreline at the southern end of this fault block, landsliding into the sea has exposed a semicircular east-facing cliff where 40m of bedded rocks crop out. Structure and stratigraphic relationships are complex in this area, but these sedimentary rocks appear to be stratigraphically higher than the aforementioned conglomeratic beds at the north end of the fault block. The cliff face rocks are not readily accessible, hence the stratigraphic thickness and lithologic data had to be estimated from a distance. The lower 25m of section, measured from sea level up the face of the cliff, consists of brown sandstone beds 0.5m to 1m thick. Similar sandstone, in beds 1 to 1.5m thick, crops out at the 25 to 30m stratigraphic level. The upper 10m of exposed section includes sandstone beds similar to those below except the beds are 10cm to 0.5m thick. About 30% of the section at this point is bedded siltstone and/or shale in beds 10 to 30cm thick. Above the cliff face vegetation covers a sequence of complexly fractured sandstone that accounts for most of
the upper surface outcrops of the fault block under
discussion. The topographic high point of this block
is 20 to 30m higher in elevation than the top of the
cliff, however, bedding is not apparent in the sandstone
and no thickness of exposure is obtainable. Thin
section analysis of this sandstone indicates a typical
feldspathic volcanic arenite classification. The rock
has 20 to 30% volcanic rock fragments, 20% feldspar
grains, and 50 to 60% quartz grains. Other accessory
sand grains are glauconite, microcline, epidote, and
metamorphic rock fragments. The rock is fine- to
medium-grained, poor- to moderately well-sorted, and
very well-indurated. A very low porosity is caused by
compaction of the rock. Compaction and partial dis-
integration has also resulted in many long-grain
contact points, deformed plagioclase and rock fragment
grains, and the presence of 1 to 3% clayey matrix.

The western slope of this southern unit m-4
fault block contains complexly faulted sandstone and
conglomerate that is probably in fault contact with the
brown sandstone mentioned above. Clasts in this western
slope conglomerate are generally larger than those at
the northeast end of the fault block, but composition
is similar. One quartzite clast 1m in diameter is
located near the peak of the fault block.
The northern exposure of rocks assigned to unit m-4 is a fault block adjacent to the islet on the east side of the island. Steep terrain precludes detailed section measuring at this locality, but an estimated 70m of bedded sandstone and conglomerate similar to the southern m-4 rocks crops out in this block. Here, the strata strike N40°E and dip westward 25 to 30°. The lower 15m of section is 70% green to red sandstone beds of 30cm average thickness, and 30% green to brownish red conglomerate lenses 15cm to 0.5m thick. About 15m above the shoreline conglomerate predominates and sandstone interbeds form only 20% of the exposure. Similar conglomerate and sandstone beds are present up to the 20m level where an estimated 50m of brown to gray sandstone with 30% lenticular interbeds of conglomerate completes the section at a point near the topographic crest of the island. Lithologically, the rocks of this northern block are nearly identical to sandstone and conglomerate outcrops in the lower 18m of section in the southern unit m-4 fault block.

A marine origin is assumed for unit m-4 on the basis of its similarity to known marine beds of South Island (units s-2, s-3, and s-4), and the close physical proximity to marine strata on Middle Island.
Unit M-5

Unit m-5 is entirely volcanic and forms the islet east of Middle Island (Fig. 20). A northwest-trending, east-dipping fault, evident at low tide, separates the islet from the bedded rocks of the main island. Even though Middle Island shelters the islet from western swells, the relatively less-resistant volcanic rock is more susceptible to wave erosion than the sediments of Middle Island proper. Except for a few tuff beds in the western half of the islet, massive volcanic breccia accounts for all of the islet's rocks.

At the extreme southwest end of the islet the bedded volcanic tuff or tuffaceous sandstone crops out in beds a few centimeters to 1m thick in an observable section of 7m total thickness. As observed from the eastern side of Middle Island (the islet is too steep to climb at this locality), bedding of these rocks strikes N15°W and dips 23°E. Similarly, on the east-west ridge at the narrow part of the islet a section of fine-grained sedimentary rocks not more than a few meters thick crops out in discontinous beds 3 to 5cm thick. These tuff beds are nearly vertical, strike N10°W, and are in fault contact with the surrounding massive volcanic breccia. No other bedding is apparent on the islet.
Figure 20. Unit m-5 Islet East of Middle Island. View is to the northeast.

Figure 21. Irregular Fault Surface on the Northeast Side of the Southern Unit m-4 Fault Block, Middle Island. View is to the southeast.
Figure 20. Unit m-5 Islet East of Middle Island. View is to the northeast.
Figure 21. Irregular Fault Surface on the Northeast Side of the Southern Unit m-4 Fault Block, Middle Island. View is to the southeast.
On the northern peninsula of the islet a fault block of basaltic flow rock crops out in a 10 square meter area. The rock is massive and no bedding is visible, but there are a few slightly deformed vesicules which suggest rock flow when molten. Since there are no pillow structures or other water indicators in the block, it is likely that it was originally deposited in a subaerial environment, and subsequently slid into the sea.

Volcanic breccia comprising the remainder and greatest portion of the islet has no apparent bedding, but the islet itself is over 20m high at its crest, thus a stratigraphic thickness well in excess of 20m is probable. This breccia exhibits angular clasts of both fine-grained andesitic basalt and basalt scoria in a greenish-brown clayey groundmass interspersed with very small plagioclase laths. The andesitic basalt clasts make up nearly 50% of the unit by volume, and range in size from small pebbles to boulders over 1m diameter. A visual estimation reveals a mean clast size of 5 to 20cm diameter. About 10% of all clasts are over 25cm diameter except in the eastern half of the islet where up to 40% of all clasts are over 25cm across.

The islet is highly fractured, though actual
faults are difficult to trace. Zones of greenish alteration in the breccia groundmass, and fault gouge are locally abundant, but usually traceable for only a few meters. Local zones rich in silica also characterize the fractured portions of the islet.

The mode of transportation and environment of deposition of unit m-5 is speculative. The tuffaceous interbeds in the breccia are typical of marine deposits found elsewhere on the Coronados. The volcanic breccia which makes up the bulk of the islet was probably deposited as a series of lahara in an area of moderate to high relief. A Marine environment of deposition is speculated on the basis of proximity (though in fault contact) to marine rocks of Middle Island and the similarity of these rocks to volcanic breccia (unit s-5) that is interbedded with marine sediments of South Island.

Geologic Structure

Tilted fault blocks with varying attitudes dominate the structural geology of Middle Island. Major faults that cut the island strike northwest or northeast, and dip to the east.

The two subparallel northwest-trending faults on either side of the island exhibit the greatest lithologic
contrast between fault blocks, and probably represent
the greatest displacement (at least 100m and possibly
much more) of any Middle Island faults. The westernmost
of these two faults separates unit m-1 rocks on the
west from unit m-2 and m-4 strata to the east. The
fault is continuous through the island with variable
strike and dip attitudes of N20°W to N30°W, 50 to 55°E
respectively in the southern part of the island and
N30°W to N35°W, 45 to 50°E near West Cove. Drag folding
just south of West Cove and secondary normal faults at
various points along the strike of the fault indicate a
normal sense of movement along this zone, at least in
the last stages of faulting. The fault zone itself is
30 to 60cm wide and composed of very well-indurated,
silica-rich, iron-stained fault gouge. Selenite
crystals are present locally on exposed surfaces of the
fracture zone. Slickensides at the West Cove area and
near the southern end of the island are subparallel to
the dip of the fault plane.

The northwest-trending fault on the east side of
Middle Island separating unit m-4 rocks from unit m-5
rocks is visible during low tide at the narrow passage
way west of the islet. The fault surface, exposed only
on the islet, strikes N10°W, dips 50°E and has
slickensides that plunge about 35° from horizontal in a
N55°W direction on the slip face. The evidence for this fault being normal is inconclusive, however, adjacent rocks to the west dip to the west and those of the islet dip locally (near the fault) to the east suggesting drag folding or rotation of the eastern block relative to the western block as normal faulting occurred. A north and south submarine continuance of this fault is inferred (Plate II).

Another major northwest-trending normal fault separates resistant and topographically high unit m-4 rocks from more eroded unit m-2 and m-3 rocks at the southern part of the island. This fault strikes N60°W and dips 75°N. Slickensides dip 40° on the fault surface in a northwest direction of plunge. Other mappable faults with a northwest strike include one just north of the previously mentioned fault, a fault at the extreme north end of the island, and two inferred faults on Middle Rock. Northeast-trending faults of Middle Island are much less conspicuous than their northwest-striking counterparts. All observed northeast-striking faults dip southeast, but no drag features or secondary faults were noted that indicate a sense of movement. An inferred fault near the island’s center traverses a structurally complex area and may in fact be a series of faults with similar
northeast trends. In addition, a portion of the eastern slope of the southern exposure of unit m-4 is itself an irregular fault surface striking N10°E to N40°E and dipping 40 to 60°E (Fig. 21). Slickensides at this locality dip 40° in a N50°E direction on the fault surface.

The strata of Middle Rock and the west side of Middle Island have a northwest strike and westward dip in accord with the general Coronado Islands bedding attitudes. The remainder of the island exhibits a wide range of east and west dips as a Result of fault block tilting and drag folding near faults.

Age of Middle Island Rocks

There is no conclusive age determination for the rocks of Middle Island, but a tentative lower to middle Miocene age is hypothesized on the basis of lithologic relationships to known Miocene rocks of South Coronado Island, southern California, and Northwestern Baja California.

The conglomerate beds in units m-1, m-3 and m-4 of Middle Island contain an abundant population of well-indurated brown, purple or pink rhyolite and/or rhyolitic tuff clasts typical of the Poway Suite. The presence of these clasts indicates an Eocene or later
age for Middle Island rocks. Also, clasts of the Catalina Schist Suite, including chlorite schist, chlorite-plagioclase schist, various mafic schists and blueschist, are interspersed in the conglomerate beds of the island. The oldest occurrence of these clasts in Tertiary rocks of the region is in conglomerate and breccia beds of the lower Miocene San Onofre Breccia near San Juan Capistrano and Oceanside (Woodford, 1925). Catalina Schist clasts are also present in rocks of the middle Miocene Rosarito Beach Formation west of Tijuana (Minch, 1967), and in similar aged rocks of South Coronado Island. The close proximity and physical similarity to middle Miocene rocks of South Island, in particular the likeness between units m-3 and m-4 of Middle Island to units s-2, s-3, and s-4 of South Island, is also evidence of a lower to middle Miocene age for Middle Island rocks.

Several samples of fine-grained Middle Island rocks collected in the present study proved to be barren of micro-fossils, but one angular, boulder-sized piece of scree material was found near the upper part of columnar section m-d that contained numerous dis-articulated pelecypod shells. The angular, blocky shape plus the lithologic similarity to surrounding rocks indicates that this rock was probably derived from a
stratigraphic layer high in the unit m-2 strata. Still, the possibility of this block being an exotic conglomerate clast or having been placed on Middle Island by human hands must not be completely discounted. According to Warren Addicott of the U.S. Geological Survey in a personal communication through Mobil Oil Company, the rock in question contained the following pelecypods; *Glycimeris* sp. -abundant, *?Pitar* ssp. -fragments, and an undetermined pelecypod, possibly *Crasselella*. Gastropods, which were present only in small numbers, are *Noticid* and *?Cylichna*. Because no hinges or entire specimens were recovered due to the hardness of the rock, a definitive identification of the fossils, or estimation of age was not possible. Addicott believes the sample to represent upper neritic depths and to be of Tertiary age. He noted that these *?Pitar* forms are characteristic of Eocene rocks in the California Coast Ranges and the Transverse Ranges. All of the Genera found, however, have ranges that extend into the Late Tertiary. The lithologic evidence of a Miocene age for Middle Island rocks is, in this case, more conclusive than the information based on non-diagnostic fossils from the one piece of float material. The Miocene age for Middle Island must remain tentative. A more concentrated hunt for dateable fossils and the
isolation and radiometric dating of glauconite in the sandstones of the island could place more conclusive boundaries on the age of Middle Island.
Chapter 4

GEOLOGY OF SOUTH ISLAND

General Statement

South Island, the largest of the Coronados, is 3.5 km long and 190 m high at Middle Peak. The island has a narrow central ridge extending its full length (Fig. 22) and steep sides that culminate at the edge of the island's perimeter in 15 to 30 m sea cliffs (Fig. 23). South Island is difficult to traverse and many areas are inaccessible, but a crude foot trail system extends the full length of the island. Three main structural blocks of westward-dipping strata comprise the island. The north and south blocks are largely San Onofre-type conglomerate and sandstone, whereas, the middle downdropped block contains conglomeratic beds similar to the north and south blocks plus volcaniclastic breccia, siltstone, and tuffaceous sandstone.

Unit S-1

Interbedded shale, siltstone, and sandstone beds make up unit S-1, the lowest stratigraphic unit of South Island. In the northeast portion of the island
Figure 22. South Island, Middle Island, and Middle Rock. View is to the south.

Figure 23. West Side of South Island. Note Middle Peak above Seal Cove. View is to the east.
Figure 22. South Island, Middle Island, and Middle Rock. View is to the south.
Figure 23. West Side of South Island. Note Middle Peak above Seal Cove. View is to the east.
these strata form a steep slope from the shoreline 45 m stratigraphically upward to their contact with the overlying, cliff-forming rocks of unit s-2 (Fig. 24). At this locality shale beds make up about 70% of the exposed outcrop and siltstone and sandstone each comprise about 15% of the section. The lower 10 m of section are dark brown, well-indurated, concretion-bearing siltstone. A few thin sandstone beds and numerous calcite-rich concretions are also present. Above the 10 m level of columnar section s-a (Fig. 25) unit s-1 is composed of alternating sandstone and shale beds. Shale layers are dark gray, well-indurated, low in porosity, and form beds 0.5 to 4 m thick. In the upper 15 m of the section the shale has shiny, undulatory parting surfaces resulting from much compaction and possibly some shearing. Sandstone interbeds are brown to light brown, fine- to coarse-grained, and poorly to moderately well-sorted. The framework grains of quartz, feldspar and volcanic rock fragments when set equal to 100% have average occurrences of 60%, 10%, and 30% respectively, giving the rock a feldspathic volcanic arenite classification. Other accessory grains in these sandstone layers are biotite, chlorite, glauconite, calcite, microcline, schist fragments, opaque minerals and sparse shell fragments.
Figure 24. Units s-1 (below contact) and s-2 on the Northeast Side of South Island. View is to the west.
Figure 24. Units s-1 (below contact) and s-2 on the Northeast Side of South Island. View is to the west.
Inaccessible cliff prevents detailed study of rocks between the 50m and 110m level.

CONGLOMERATE: light gray, calcite bearing, medium to coarse grained, angular, very poorly sorted, very well indurated, low to moderate porosity, massive, widespread scouring into shale beds below, numerous groove casts, flute casts, and chatter marks, clasts are 1cm to 70cm diameter. Sandstone interbeds are light greenish gray, medium to coarse grained, and lenticular. Between the 55m and 100m level conglomeratic sandstone in beds 50cm to 50cm thick makes up about 70% of the section.

SANDSTONE: brown, calcite bearing, fine to medium grained, poor to moderately well sorted, well indurated, low porosity, beds 3cm to 10cm thick, lenticular and irregular.

SILTY SANDSTONE: grey, calcite and selenite bearing, well sorted, well indurated, very low porosity, very fissile, some calcite-rich concretions.

SANDSTONE: light brown, calcite and iron oxide bearing, fine to medium grained (fine grains predominate), subangular, moderately well sorted, very well indurated, moderate porosity, beds are 0.3cm to 10cm thick, wavy and discontinuous.

SANDSTONE: brownish gray, calcite and calcite-rich concretion bearing, well sorted, well indurated, moderate porosity, weathered rock in very fissile and brown, grades into sandy siltstone above.

SANDSTONE AND SILTSTONE: (interbedded): Sandstone is light brown, mica bearing, fine grained, well sorted, very well indurated, moderate porosity, beds 0.5cm to 3cm. Siltstone is gray, well sorted, well indurated, moderate porosity, beds 0.5cm to 3cm.

SANDSTONE: green, calcite and green alteration mineral bearing, medium to coarse grained, angular to subangular, poorly sorted, very well indurated, low porosity.

SILTSTONE: dark brown, calcite and calcite-rich concretion bearing (concretions are 10cm to 30cm diameter), well sorted, very well indurated, low porosity, massive, grades to shale above.

Sandstone and sandy conglomerate matrix of this section are feldspathic volcanic arenites. The classification scheme of Folk (1963) is used.

Figure 25. Columnar Section s-a. See Plate III for traverse route.
An exposure of shale and sandstone similar to the rocks discussed above crops out under a vertical cliff near the shoreline 30m south of the landslide debris on the eastern margin of the island (Plate III, backpocket). Here, 1.5m of shale and interbedded sandstone crop out beneath a thick section of unit s-2 conglomeratic sandstone and conglomerate. The shale is black to gray, moderately well-indurated, has 2mm to 30cm thick beds, and as in the northern unit s-1 shales, exhibits shiny fracture surfaces subparallel to the bedding. Sandstone interbeds are thin, light gray to brown, fine-grained, well-sorted and well-indurated. The author is reasonably sure that this small outcrop correlates stratigraphically with the upper few meters of unit s-1 shale at the north part of the island. The most conclusive evidence is in the characteristic abrupt change in lithology from fine-grained shale of unit s-1 to the coarse deposits of overlying unit s-2. Also, sedimentary structures on the base of unit s-2 rocks (described below) are of a similar nature and show the same general current directions at both localities.

The sediments of unit s-1 were deposited in a marine environment as indicated by Foraminifera obtained from the shales by the author and previous workers.
Generally quiet conditions accompanied deposition of the shale beds with periodic influxes of sand transported by currents.

**Unit S-2**

Overlying the fine-grained deposits of unit s-l is a thick, cliff-forming section of sandstone and conglomerate. Unit s-2 accounts for about two-thirds of the total volume of South Island. No detailed section measurement was undertaken in this study due to the extreme steepness of the island wherever these rocks crop out. As a result, thickness quotations are visual estimates. An incomplete section 60m thick crops out at the north end of the island, and the southern two-thirds of the island is composed entirely of about 250m of these coarse deposits. The top of South Peak marks the highest stratigraphic exposure of unit s-2. If additional rocks exist further up section they may crop out on the ocean bottom several tens of meters west of the present shoreline.

Woodford (1925) compared these rocks to those of the San Onofre Breccia type locality 100km to the north near Oceanside, California. This likeness includes the general coarseness of both deposits, and the presence of Catalina Schist clasts in the sediments.
Although the unit s-2 rocks may be a southern equivalent of the San Onofre Breccia, the San Onofre rocks at their type locality contain a red muddy matrix suggesting mudflow deposition. The rocks of South Island show much evidence of current deposition and submarine movement.

The base of unit s-2 in the northern part of the island is evident on the geologic map (Plate III), however, the contact between units s-1 and s-2 30m south of the landslide debris on the east side of the island is masked by a vertical cliff, preventing a map view of the contact. These north and south outcrops of the lower few tens of meters of unit s-2 are nearly identical in composition, fabric and topographic expression. At both localities steep, east-facing cliffs 30 to 50m high display coarse clastic deposits.

In the southern area of outcrop the lower 20m of section is 80% conglomeratic sandstone, 10% pebble-bearing sandstone, and 10% conglomerate, as estimated visually from the base of the cliff. The lower 5m is pebbly sandstone grading upward to conglomeratic sandstone. As a whole this sandstone is light green, medium- to coarse-grained, poorly sorted, well-indurated and forms beds 15cm to 4m thick. Bedding is lenticular, but beds of 1m or greater thickness extend laterally for 7 to 45m. The majority of conglomerate lenses are
1 to 6m thick and all contain a typical suite of clasts that include, in order of decreasing abundance, quartz-chlorite schist, quartz-amphibole schist, quartzite, vein(?) quartz, chlorite-garnet schist, blueschist, rhyolite, sandstone and siltstone. Clasts commonly make up 30% or more of the conglomerate lenses by volume. The various schists and quartz-rich rocks account for 90% of the clast population, sandstone and siltstone 5%, rhyolite 2% and all others 3%. Most clasts are subrounded to rounded and 5 to 20cm in diameter. Only a very small percentage of clasts are over 30cm diameter.

Analogous rocks of the lower part of unit s-2 comprise a cliff on the northeast side of the island near the west terminus of columnar section s-a (Plate III). Massive pebbly sandstone is the major rock type in the lower 6m of section at this locality. Further up the cliff, conglomeratic sandstone and conglomerate in beds 30cm to 2m thick crops out in a section of 55m stratigraphic thickness extending to the crest of the island. In this outcrop sandstone beds and the conglomerate matrix material are light gray to green, medium- to coarse-grained, poorly sorted, well-indurated feldspathic volcanic arenites. A clayey matrix that makes up 3 to 10% of the sandstone accounts for the low
porosity and extreme toughness of the rock. Conglomerate clasts are similar in composition, abundance and variety to those low in the section in the southern half of the island. Clast sizes range, in a more or less even distribution, from 3 to 40cm diameter.

The upper 200+m of unit s-2 rocks, which are not exposed in the northern half of the island due to faulting and/or erosion, are present in the southern main fault block of the island. The thickest continuous section is east of South Peak where an estimated 250m of conglomerate and conglomeratic sandstone crop out. The section is marked by subequal percentages of interbedded sandstone, conglomeratic sandstone, and conglomerate. No direct measurement or sequential rock descriptions were undertaken in this area because of the steep terrain, but spot descriptions of these rocks were obtained at various accessible locations. At the crest of the island near its narrowest part on the south block at a point estimated at 120m stratigraphically above the base of the unit, conglomeratic beds are 30cm to 3m thick, and are green in color with a slightly higher percentage of rhyolite and andesite clasts as compared to other clasts previously described near the bottom of the section. A sandstone sample from this locality observed in thin section is a green,
medium- to coarse-grained, poorly sorted, angular, well-indurated feldspathic volcanic arenite. When placed equal to 100%, the percentages of quartz, feldspar and rock fragments of this particular sample are 33%, 30%, and 37% respectively. At least 95% of the rock fragments are volcanic, and the remainder are schists, sandstones and a few plutonic grains. Minor constituent minerals incorporated in the thin section sample are mica, glauconite, microcline, interstitial calcite, and chlorite alteration in the matrix and in some volcanic rock fragments. Calcite has partially replaced some quartz grains and phenocrysts in volcanic rock fragments. About 10% of the rock is green to red clayey matrix that is probably a pseudomatrix derived from decomposed volcanic rock grains. Post-depositional compaction is evident from the many contorted mica grains and schist fragments.

A sandstone interbed located at the 180m stratigraphic level near the south lighthouse (Plate III) was also analyzed in thin section. A feldspathic volcanic arenite classification is again employed for this brown, medium-grained, angular, moderately well-sorted, and well-indurated sandstone. The three main fabric constituents when assumed to equal 100% of the rock are quartz 40%, feldspar 25%, and rock fragments (nearly all
of which are volcanic) 35%. Present as accessory minerals are chlorite alteration of some volcanic grains, interstitial hematite(?) crystals, and unidentified opaque minerals. A reddish-brown ferric oxide clayey cement or pseudomatrix makes up about 10% of the sample. Mica grains are commonly crushed to varying degrees and many volcanic rock fragments have deformed from pressing against harder feldspar and quartz grains during post-depositional compaction.

East of South Peak at the 150 to 200m stratigraphic level (measured from sea level) there is a somewhat larger percentage of pebbly sandstone as opposed to conglomeratic beds. In this zone, which extends laterally for 70m or more, conglomeratic beds are only 30% of the total outcrop. At the crest of South Peak the sandstone and conglomerate beds are about evenly distributed, and are typical of rocks at the base of the unit described earlier in this report except that a greater percentage of sedimentary clasts are incorporated in the conglomerate. These shale and fine-grained sandstone clasts ranging in size from 3 to 30cm make up 5% of the clast population.

Thin section analysis of sandstone interbeds from near the crest of South Peak reveals up to 50% rock fragments (mostly volcanic), 25% quartz, and 25%
feldspar on a 100% total basis. Biotite, interstitial chlorite alteration, calcite spar, and unidentified opaque minerals are also interspersed throughout the rock. Grains are medium- to coarse, poorly sorted, angular to subangular, very well-indurated and low in porosity. Calcite spar cement comprising up to 5% of the total thin section, accounts for the rock's extreme toughness and low porosity. Post-depositional compaction was pronounced in these rocks as many grains of mica, as well as rock fragments and feldspar, are fractured, contorted, or indented by neighboring grains.

Sedimentary structures related to water currents were observed in unit s-2 deposits, mostly in the lower part of the section and at the contacts between unit s-2 and unit s-1 rocks. Where exposed at the northeast part of the island and just south of the landslide debris on the east side of the island, the contact between unit s-1 and s-2 is sharp, somewhat irregular and is made obvious by the contrast between the dark shale of unit s-1 against the lighter colored coarse sandstone of unit s-2. At both contact localities the softer shale of unit s-1 has been differentially eroded relative to the cliff-forming unit s-2 sandstone, leaving overhangs that partially expose the underside of the initial unit s-2 deposits (Fig. 26). Sedimentary
Figure 26. Flute Casts on Bottom of Unit s-2 on Northeast Side of South Island. View is upward to the southwest.

Figure 27. Sandstone, Conglomerate, and Fossil Burrows of Unit s-3 at Shoreline West of Puerto Cueva Cove. View is to the west.
Figure 26. Flute Casts on Bottom of Unit s-2 on Northeast Side of South Island. View is upward to the southwest.
Figure 27. Sandstone, Conglomerate, and Fossil Burrows of Unit s-3 at Shoreline West of Puerto Cueva Cove. View is to the west.
structures such as chatter marks, roll marks, groove casts, flute casts, and scours associated with pebbles, are present as raised surfaces on the bottom of unit s-2. At the southern units s-1-s-2 contact south of the landslide debris the most diagnostic current indicators are pebble-associated scour marks 1 to 2cm deep, 2 to 5cm wide, and 5 to 15cm long with tails that point due north to N10°W. There are also flute casts 1 to 3cm deep, 3 to 10cm wide, and 5 to 30cm long that indicate a N10°W current direction. Chatter mark patterns up to 4m long are oriented N10°E (or 310°W) at this cliff overhang. One roll mark was caused by a subrounded object rolling in either a N80°W or S80°E direction.

The bottom of unit s-2 rocks at the north exposure includes pebble scours oriented N10°E to N20°E that are 2 to 4cm wide and 5 to 15cm long, flute casts 1 to 3cm deep, 3 to 15cm wide, and 15cm to 0.5m long that point N5°E to N10°E (Fig. 26), and nondiagnostic groove casts oriented N5-10°E (or S5-10°W). The strike and dip of strata from which the above readings were taken is N10°W, 33°W at the northern end of the island and N15°W, 12°W at the cliff south of the landslide debris. Assuming that simple post-depositional rotation has tilted these beds, a reconstruction to a subhorizontal position would impart only a few degrees of
additional easterly component to the observed paleo-current directions.

Two sets of cross-beds are evident on the cliff above the unit s-1-s-2 contact south of the landslide debris. One set, 1m long, crops out on a north-facing cliff 5m above the contact with unit s-1. These cross-beds have an apparent easterly dip of 20° in a N80°E direction. About 4m above the unit s-1-s-2 contact on the large east-facing cliff cross-beds on the order of 4 to 10cm thick and 2 to 4m long have apparent dips of 15 to 25°N (Fig. 28). This cross-bed sequence is 1.5m in total thickness and is continuous for 10m laterally.

About 150m to the south near the shoreline, a conglomerate-filled channel 1m across and scoured into sandy beds, appears to be oriented roughly north-south. Other channels are present in unit s-2 conglomeratic beds, but none were observed in sufficient three-dimensional perspective to obtain channel directions.

Sedimentary structures observed farther up section in unit s-2 are rare and nondiagnostic except for a pebble-related scour on the underside of a cliff located west of South Peak along a trail leading to South Lighthouse. The sand around the pebble trails off in a N5°E direction. A 0.5m long groove cast at the same location is oriented N10°E. This indicates at
Figure 28. Cross-beds of Unit s-2 South of Unit 1s on East Side of South Island. Vertical field of view is 4m. View is to the southwest.
Figure 28. Cross-beds of Unit s-2 South of Unit ls on East Side of South Island. Vertical field of view is 4m. View is to the southwest.
least some northward current movement was occurring while rocks at the 120m stratigraphic level of unit s-2 were being deposited.

Thus, the abrupt influx of coarsely clastic unit s-2 debris over the unit s-1 shales was at least partially transported by currents. Cobble and boulder-sized clasts, together with large-scale cross-beds in the strata attest to moderately strong current velocities. North-northeast-flowing currents were dominant, at least during deposition of the lower few meters of unit s-2. Although no slope indicating structures were located, a slope component of undetermined attitude probably had an influence over transport of conglomerate clasts, some of which are up to 0.5m diameter.

Unit S-3

The southern border of unit s-1 and s-2 in the north part of the island is an east-dipping fault. Normal movement approximating dip slip has been of major importance on this fault, as indicated by secondary normal faulting, slickensides and drag folding. Hence, rocks directly to the south of the fault (unit s-3) have been down faulted from a position stratigraphically above unit s-2. Likewise, two small fault blocks southeast of North Lighthouse have been
caught as fault slices between unit s-2 rocks and the main down dropped central fault block of the island (Plate III). These smaller fault blocks cannot be positively correlated with the unit s-3 rocks to the west, but both outcrops appear to lie stratigraphically between units s-2 and s-4.

The main block of unit s-3 rock west of Puerto Cueva Cove is composed of 85m of interbedded sandstone, conglomerate, and siltstone that strikes north-south to N10°W and dips 23 to 34°W. Columnar section s-b (Fig. 29) typifies the northern half of the block. The lower 40m of these unit s-3 rocks is largely interbedded sandstone and conglomerate lenses. Sandstone interbeds and the conglomerate matrix are gray to brown, fine- to coarse-grained, angular to subangular, poorly sorted, well-indurated, feldspathic volcanic arenites.

The following analysis is from a thin section of sandstone from the 12m level of section s-b. In this sample quartz, feldspar and rock fragment grains, when set equal to 100% yield an estimated 45% quartz, 20% feldspar, and 35% rock fragments. The rock fragment population is about 90% volcanic, 5% metamorphic, and 5% sedimentary, plutonic and unrecognizable fragments. Approximately one-third of the volcanic rock grains show spotty chlorite alteration. Interstitial calcite
Top of section is terminated by a northeast trending normal fault.

**SANDSTONE:** brown, thin bedded.

**SHALEY SILTSTONE:** similar to shaley siltstone below.

**SILTY SANDSTONE:** brown.

**SHALEY SILTSTONE:** yellowish-brown, mica bearing, well sorted, moderately indurated, low porosity, massive, weathers blocky in 2cm to 5cm chips.

**SILTY SANDSTONE:** brown.

**SHALEY SILTSTONE:** similar to shaley siltstone above.

**SANDSTONE:** brown, beds 30cm to 3m thick.

**SANDSTONE:** brown, massive.

Inaccessible cliff prevents detailed study of rocks above this level.

**CONGLOMERATE:** similar to conglomerate described below, some discontinuous sandstone lenses.

**SANDSTONE:** light brown, calcite, pebble and cobble bearing, fine to medium grained, subangular, moderately sorted, low porosity, beds 10cm to 50cm thick.

**SANDSTONE, CONGLOMERATE, SILTSTONE AND SHALE, (interbedded):** Sandstone, dark brown to brown, calcite bearing, fine to medium grained, subangular, moderately sorted, moderately indurated, medium porosity, beds 10cm to 1m thick. Conglomerate, similar to conglomerate described below. Siltstone, brown, calcite bearing, well sorted, well indurated, low porosity, beds 3cm to 10cm thick. Shale, dark gray, calcite bearing, well sorted, well indurated, low porosity, beds 2cm to 15cm thick.

**SANDSTONE AND CONGLOMERATE, (interbedded):** Sandstone, gray to brown, calcite and cobble bearing, fine to medium grained with a few medium to coarse grained beds, angular to subangular, poorly to moderately sorted, well indurated. Low porosity, rhythmic beds 10cm to 100cm thick, lenticular beds 3m to 25m long. In outcrop, some lenses grade into conglomerate, some crossbedding and scoured of underlying beds, less resistant than conglomerate. Conglomerate, Matrix: gray, calcite bearing, fine to granular grained, subangular, very poorly sorted, very well indurated, low porosity. Clasts, 2cm to 20cm diameter, angular to rounded. Most clasts are subangular but some resistant (and possibly reworked) metavolcanic and quartz-rich clasts are rounded to well rounded, clasts include fine grained quartzite, quartz, altered green volcanic rock, rhyolite, or metatuffolite, hornblende andesite, mica schist, quartz-mica schist, well indurated green sandstone, conglomerate beds are 10cm to 1m thick, 15cm to 30cm thick beds most common, some scoured of underlying sandstone beds.

Figure 29. Columnar Section s-b. See Plate III for traverse route.
is scattered throughout the rock, and together with a clayey hematitic cement, cause the rock to be well-indurated. Due to compaction after deposition, many volcanic rock fragments have deformed passively when pressed against harder quartz and feldspar grains.

Bedding in these sandstone layers is in the form of lenses 3 to 30m long with individual beds 5cm to 0.5m thick. Many sandstone beds grade laterally into conglomerate. Clasts in the conglomerate lenses range in size from small pebbles to boulders over 40cm diameter. A typical outcrop yields clasts of quartzite, vein(?) quartz, quartz-rich schist, well-indurated green sandstone, hornblende schist, mica schist, quartz-amphibole schist, rhyolite, and altered green volcanic rocks. Softer schist clasts are subangular to sub-rounded, whereas, harder quartz-rich and volcanic rocks are generally rounded to well rounded. Conglomerate beds are also lenticular and 5cm to 1m in thickness with 10 to 30cm beds being most common. Scouring of underlying sandstone interbeds is widespread. The abundance of conglomerate relative to sandstone in the area, represented by columnar section s-b, is 80% in the lower 20m (measured stratigraphically from sea level), grading to about 50% in the 20 to 40m level. Conglomerate diminishes to about 10% of the total
outcrop above the 50m stratigraphic level. A trend toward finer overall grain size begins about the 25m level in the section with the presence of two shale-siltstone beds that vary in thickness from 2cm to 15cm. The shale is dark brown to brown, with a calcite cement and strong induration. Some siltstone beds are up to 1.5m thick. The upper half of columnar section s-b contains massive shaley siltstone beds up to 15m thick, and interbedded brown silty sandstone. Inaccessibility of outcrops and the thick vegetation cover precluded detailed observation of the upper half of section s-b.

Lateral equivalents of the section s-b conglomerate sandstone interbeds crop out along the shoreline south of the traverse route. Two east-west-trending faults west of Puerto Cueva Cove border a fault block that appears to have been down-dropped relative to the main body of unit s-3 rocks. Most of the strata of this fault block are fine grained and may be a down-dropped lateral equivalent of the upper part of the strata in section s-b. The fault block has 30m of exposed section on a steep east-facing slope. Starting from the shoreline and proceeding up section, there are 6m of interbedded conglomerate and sandstone, 20m of massive siltstone with sandstone interbeds and discontinuous sandstone lenses in beds 3 to 10cm thick.
Above the 25 to 30m level a resistant section of sandy conglomerate crops out where the slope of the island becomes more gentle. This conglomerate is at least 3 to 4m thick in exposed outcrop, but soil cover masks all outcrops upward and westward to the crest of the island. At the island's crest a similar conglomerate crops out. This discontinuously outcropping conglomerate may be stratigraphically higher than the top of columnar section s-b to the north. These conglomeratic layers along the crest of the island continue down the steep western slope and southward where they form a southwest-pointing peninsula on the west side of Seal Cove. The outcrop at Seal Cove is conglomerate and sandstone interbeds, typical of those near the shoreline on the west side of Puerto Cueva Cove, but no direct correlation has been made. In general the fabric and composition of conglomerate beds at both localities is similar except for the presence of an amphibole schist clast at Seal Cove which measures over 1m in diameter.

On the east side of the island two small fault slices southeast of North Lighthouse contain sandstone, conglomerate, and siltstone similar in nature to the lower 40m of unit s-3 rocks west of Puerto Cueva Cove and east of North Peak. A unit s-3 designation has been assigned to these rocks because they are
stratigraphically intermediate between unit s-4 of the central fault block and unit s-2 rocks that are relatively up-faulted in the immediate area. Strata of the southern unit s-3 fault block along the eastern shoreline strike N45°W and dip 15°SW. This fault block has the most westerly component of strike of any strata on South Island. Here, an eroded cliff reveals about 25m of interbedded coarse and fine-grained clastic sediments. Near sea level a layer of green siltstone 2m thick underlies a light gray to brown sandstone bed 0.5m thick. Microscopic observation of these rocks reveals fine- to medium, angular and poorly sorted grains. By setting the quartz, feldspar and rock fragment content equal to 100% an average spread of 50% quartz, 15% feldspar, and 35% rock fragments is obtained. Nearly all rock fragments are volcanic. There are also scattered grains of schist, microcline, and mica. Interstitial calcite comprises about 4% of the rock and together with a clayey red cement causes the rock to be very tough. Some quartz grains show evidence of partial replacement by calcite. The upper 22m of this section is 90% interbedded conglomerate and sandstone with beds commonly 0.5 to 3m thick. The other 10% is thin layers of siltstone and shale 3 to 30cm thick which are interspersed more or less evenly.
Vegetation and rock fall debris covers any continuation of this section upward and/or to the west.

The fault slice adjacent to and north of the above section is also partially masked by vegetation and soil-rock debris. However, 3 to 10m of interbedded conglomerate, sandstone, and tuffaceous sandstone are exposed along the shoreline. Sandstone and conglomerate layers are similar to those near the bottom of columnar section s-b. The interbedded tuffaceous sandstones are pink to purple, fine- to medium-grained, and lenticular.

Sedimentary structures that reflect paleoslope directions are abundant in unit s-3 rocks. Along the east-facing shoreline south of columnar section s-b interbedded sandstone and conglomerate layers contain flame structures, channels, convolute bedding, deformed load casts and rip-up structures. These features are generally less than 1m across. In most cases a finer-grained sandstone or siltstone bed has been overlain and disturbed by coarse-grained sandstone or conglomerate. Nearly all of these structures indicate a strong northward component of paleoslope at the time of deposition. The northward slope indicators may be prejudiced, however, by the occurrence of most structures as two-dimensional east-facing outcrops. In most cases east or west components of slope could not be
determined.

Not enough cross-beds of a measurable nature were observed to speculate on average current directions at the time of deposition, but two well-developed cross-bedded sandstone layers indicate an east to northeast-flowing paleocurrent. Scouring of relatively fine-grained underlying beds nearly always proceeded or accompanied deposition of conglomerate or coarse sandstone in the area.

The two fault blocks assigned to unit s-3 southeast of North Lighthouse also exhibit sedimentary structures, mostly near the present shoreline. Features from which no conclusive paleoslope determinations were discernable include load casts, scouring, channeling where coarse-grained lenses overlie fine-grained rocks, and convolute bedding in fine-grained deposits. Most sedimentary structures observed in the area were 0.5 to 1m in lateral extent. Two exceptions are a rotated slump block of fine-grained bedded sandstone 2.5m long (Fig. 30), and a rip-up clast of tuffaceous siltstone 2m long and 30cm thick (Fig. 31). Shortly after deposition coarse sand layers overlying the fine-grained sediments were set in motion and ripped up the underlying silt and tilted the still-soft sediment northward. An overall evaluation of sedimentary structures suggests
Figure 30. Slump Block in Unit s-3 Sandstone. View is to the southwest.

Figure 31. Sandstone Rip-up in Unit s-3 Conglomerate. View is to the west.
Figure 30. Slump Block in Unit s-3 Sandstone. View is to the southwest.
Figure 31. Sandstone Rip-up in Unit s-3 Conglomerate. View is to the west.
that a northerly paleoslope was present when unit s-3 sediments were deposited.

Foraminifera of middle Miocene age have been recovered from siltstone deposits in the first fault block to the south of the columnar section s-b traverse. The reader is referred to the section of this report regarding the age of South Island for more detailed discussion of these fossils. Near the shoreline west of Puerto Cueva Cove several fossil burrow casts are located in sandstone interbeds of the largely conglomeratic deposits of the area (Fig. 27, p. 86).

The lower 30m of unit s-3 rocks west of Puerto Cueva Cove were deposited in a marine environment with periodic strong currents and a northward ocean floor slope. The upper 45m of shaley siltstone and silty sandstone suggest a quieter environment of marine deposition. A change in the type of sediment available may have been a primary factor in this change in grain size. The conglomeratic rocks at the crest of the island in this unit s-3 area again reveals high energy depositional conditions, but no additional clues as to depositional environment were found.

Similar conditions of strong currents and a northerly paleoslope prevailed during deposition of unit s-3 sediments southeast of North Lighthouse. If
these deposits are not contemporaneous with those to the west across the cove, the two outcrops, separated by a major down-dropped block, at least represent instances of similar depositional environment during the span of geologic time between deposition of unit s-2 and unit s-4.

**Unit S-4**

Unit s-4, with the exception of a volcaniclastic bed in the upper part of the unit, is composed of 40m of conglomeratic sandstone and conglomerate similar to deposits of unit s-2 and the lower and upper portions of unit s-3. These rocks are the lowest stratigraphic beds exposed in the main down-dropped (but topographically high) fault block forming the central part of the island. Unit s-4 rocks are somewhat more resistant than the overlying strata of the fault block, and have resisted wave erosion. They comprise the peninsula on the east side of Puerto Cueva Cove (Plate III). These rocks (excepting the terrace deposits) strike N15°E to N20°E and dip 25 to 35°W. The western half of the peninsula is a dip slope except near the shoreline where cliffs 3 to 5m high have developed. Unit s-4 rocks are in fault contact with unit s-3 at the surface southeast of north lighthouse and probably rest in
CONglomeratic Sandstone: light brown, calcite bearing, fine to grit grained, angular, poorly sorted, very well indurated, low porosity, beds 15cm to 1m thick (30cm to 50cm beds are most common). Clasts, 2cm to 15cm diameter, approximate percentages of clast types are quartz, quartzite, vein quartz and quartz-rich schists 30%, green or brown sandstone 20%, amphibole schist and mica schist 15%, rhyolite and other volcanic rocks 10%, chlorite schist, blueschist, and other metamorphic rocks 5%.

Volcaniclastic Breccia: Matrix, brown, calcite bearing, fine to granular grained, angular, very poorly sorted, well indurated, low porosity, massive, matrix classified as a mudstone consisting of altered badly weathered volcanic rock fragments, plagioclase crystals, quartz grains and altered clay. Clasts are all weathered andesite, angular, 1cm to 0.5cm diameter, well indurated though weathered, clasts make up 50% of the bed.

Conglomerate: similar to the conglomerate described below except for a smaller general clast size, clasts 2cm to 10cm diameter are most common with a few clasts 20cm or greater in diameter, clasts constitute 20% to 30% of the beds in the 15m to 32m level, pebbly sandstone lenses are interspersed in the conglomerate, individual beds of conglomerate and sandstone are lenticular, 10cm to 1m thick and 2m to 15m long in outcrop.

Sandstone: light brown, calcite, pebble and cobble bearing, fine to coarse grained, angular, very poorly sorted, very well indurated, beds 15cm thick, locally graded from coarse grained near the bottom to fine grained near the top of the 0.5m bed, some load casts and small flame structures in interbedded paper thin siltstone layers.

Conglomerate: Matrix, greenish gray, calcite bearing, fine to grit grained, angular, very poorly sorted, very well indurated, low porosity, massive with a few pebbly sandstone lenses 15cm to 30cm thick, sandstone is less resistant than conglomerate, Clasts, 2cm to 15cm diameter (most clasts are 5cm to 15cm diameter), angular to rounded (only the more resistant and possibly reworked metavolcanic and quartz-rich rocks are rounded), clasts make up 60% to 70% of the section in the 1m to 1.5m level of the section, clasts include quartzite, vein (?) quartz, quartz-rich mafic schist, rhyolite, green chlorite schist, mica schist, and blue schist.

*Sandstone and sandy conglomerate matrix of this section are feldspathic volcanic-arenites. The classification scheme of Folk (1968) is used.

Figure 32. Columnar Section s-c. See Plate III for traverse route.
fault contact with unit s-2 at depth in the same general area.

Columnar section s-c (Fig. 32) represents a traverse of the total thickness of unit s-4. The section begins at the lowest stratigraphic level possible at a point on the shoreline east of north lighthouse. The lowest subaerial exposure at this point is a conglomerate bed 7.5m thick with 60 to 70% clasts by volume (Fig. 33). Typical clast types for this bed and other unit s-4 conglomerate beds as well are quartzite, vein(?) quartz, quartz-bearing mafic schist, rhyolite, green altered volcanic rock, andesite, coarse sandstone, amphibole schist, chlorite schist, mica schist, and blueschist. Clast size is variable from small pebbles to boulders over 1m in diameter, though most clasts are in the 3 to 15cm range. The largest clast found in unit s-4 conglomerate beds is a blueschist clast about 1.5m in diameter located at the shoreline near the southern contact with unit s-3 beds (Fig. 34). Clasts of schist, sandstone and other moderately nonresistant rocks are subangular to subrounded, whereas, very resistant clasts with a high quartz content, and metavolcanic rocks are commonly subrounded to well rounded. Pebbly sandstone lenses 15 to 30cm thick are spaced throughout the conglomerate
Figure 33. Conglomerate of Lower Part of Unit s-4 East of North Lighthouse. Note 1.5m Diameter Amphibole Schist Clast to left of Geologist. View is to the northwest.

Figure 34. Blueschist Clast of 1m Diameter in Unit s-4 Near Shoreline East of North Lighthouse.
Figure 33. Conglomerate of Lower Part of Unit s-4 East of North Lighthouse. Note 1.5m Diameter Amphibole Schist Clast to left of Geologist. View is to the northwest.
Figure 34. Blueschist Clast of 1m Diameter in Unit s-4 Near Shoreline East of North Lighthouse.
outcrop. In thin section the percentages of major constituents are quartz 11%, feldspar 27%, and rock fragments 62%. These sandstone lenses are classed as green to gray, fine- to coarse-grained, angular to subangular, poorly to moderately sorted, well-indurated feldspathic volcanic arenites. Volcanic pieces make up 70% of the rock fragments and the remaining 30% are metavolcanic fragments, schist, sandstone and some plutonic grains. The volcanic rock fragments are generally intermediate to rhyodacitic in composition. Over 95% of the feldspar grains in the slide examined are plagioclase and most of these are sericitized or saussuritized. Nearly 20% of the sample is a clayey matrix, which may have developed post-depositionally from decomposition of volcanic rock fragments. Calcite spar fills most voids in the rock and has replaced portions of about 75% of all quartz grains. Post-depositional compaction is evident from the draping of matrix around sand grains, deformation of mica, and intraclast grains, and the penetration of softer volcanic rock fragments by other grains.

Above the aforementioned conglomerate and sandstone lies a bed of sandstone 0.5m thick. Although actually an interbed in conglomerate, the bed is noteworthy in that it is laterally continuous for
several tens of meters and represents a period of finer-grained, quiet deposition. This sandstone is coarse-grained near the bottom, but grades to fine- to medium-grained in the upper 20 cm of the bed. Paper-thin layers of silty material in the sandstone attest to a time of quiet, fine-grained deposition. Load structures caused by pebbles, flame structures and miniature convolute folding are made visible by these thin silty layers. These sedimentary structures do not reveal a preferred slope direction.

Continuing up the section s-c traverse there is 6 m of conglomerate and sandstone interbeds, for the most part identical to those below the laterally continuous sandstone bed. At this level the percentage of clasts declines as does the average size of conglomerate clasts. The average clast size for these beds is 2 to 10 cm with rare clasts of 20 cm or greater diameter. Whereas clasts constitute 60 to 70% of the beds lower in the section, their presence by volume in this 14 to 32 m level is about 20 to 30%. Volumetrically, the conglomerate comprises 90%, and pebbly sandstone 10% of this portion of the section. Bedding thickness for the lenses of both rock types is variable between 10 cm and 1 m. The only sedimentary structures noted in these beds are load structures in sandstone caused by
the downward pressing of overlying clasts.  

At the 32m level in section s-c is an outcrop of volcaniclastic breccia 2.5m thick. As noted in previous rock descriptions there is a heavy volcanic influence on the lithology of South Island, but this bed is the lowest stratigraphic occurrence of a true volcaniclastic bed. The breccia is in sharp contrast with the underlying and overlying conglomerate. The outcrop can be traced along strike for at least 20m southward, but weathering and a thin soil cover make it difficult to trace this bed further. Overall, the breccia is about 50% clasts and 50% clayey, sandy matrix. The groundmass of this water-deposited breccia is composed of altered and badly weathered volcanic rock fragments, plagioclase crystals, quartz grains, other unidentified grains, and somewhat altered clay, most probably derived post-depositionally from decomposing rock fragment grains. The rock is very poorly sorted, well-indurated, and has low porosity. Being more susceptible to weathering than the surrounding conglomeratic rocks, the matrix crumbles easily when wet. Clasts are exclusively volcanic, are angular to subangular, and range in size from 3cm to 0.5m diameter. Hand specimen identification of the rock indicates an andesitic composition. Secondary growths
in the clasts include opaline vug fillings, whereas the groundmass has veins of calcite spar.

The upper 10m of unit s-4 is bedded conglomerate and conglomeratic sandstone. The top of these beds forms a dip slope on the western half of the peninsula north of north lighthouse. As in conglomeratic beds below the volcanic breccia unit, clasts make up 10 to 30% of individual lenses. Bedding thicknesses range from 15cm to 1m with 30cm to 0.5m beds being commonest. Clast size is 2 to 15cm. A megascopic description of clast types and estimated percentages are 50% quartz, quartzite, and quartz-rich schists, 20% green or brown sandstone, 15% amphibole schist and mica schist, 10% rhyolite and other volcanic rocks, and 5% chlorite schist, blueschist, and other metamorphic rocks. The sandstone beds and conglomerate matrix, as determined from hand specimen and thin section analysis, is light brown, fine- to grit-grained, angular to subangular, very poorly sorted, very well-indurated feldspathic volcanic arenite. Minor constituent grains include chlorite, various opaque minerals, mica, and microcline. Calcite fills voids between grains and makes up 1 to 2% of the rock. Proportions of the three major grain types are quartz 35%, feldspar 15%, and rock fragments 50%. Except for a few percent of metamorphic and
sedimentary grains, all rock fragments are volcanic. A clayey matrix, made up in part of decomposed volcanic rock fragments, comprises over 30% of the rock. Many badly weathered volcanic grains are barely distinguishable from the matrix material. Post-depositional compaction is evidenced by crushed grains of plagioclase, sedimentary rock fragments, and mica.

A marine environment of sedimentation is assumed for unit s-4 on the basis of known marine strata cropping out stratigraphically below (though in fault contact) and above the unit. Conglomerate deposits, at least those representative of the lower 15m of section, are coarse and contain a few boulders more than 1m in diameter. These boulders were almost certainly transported by means other than ocean bottom currents. Submarine slumping is the most logical explanation for transport of these large clasts. The provenance of unit s-4 was partly volcanic as indicated by the laying down of an exclusively volcanoclastic bed within conglomeratic deposits.

Unit S-5

Unit s-5 is a volcanoclastic breccia 45 to 50m thick conformably overlying unit s-4. On the east side of the island this breccia crops out at the southwest
end of Puerto Cueva Cove on a vertical northeast-facing cliff and forms a small sea stack at the south end of the cove. Lateral equivalents on the west side of the island crop out along the north and east edges of Seal Cove. Unit s-5 dips westward 20 to 30° in accord with the other conformable strata of the main central fault block of the island.

At the Puerto Cueva exposure (represented by columnar section s-d, Fig. 35) the unit s-5 groundmass is greenish brown to dark green, feldspar-bearing, clayey mudstone, the bulk of which is derived from a volcanic source. Only a few quartz grains were located in the groundmass. The predominance of green chloritic (?) clay in the matrix may have resulted from decomposition of volcanic rock fragments. This matrix is low in porosity, well-indurated when dry, but crumbles easily when wet. The proportion of clasts to matrix is about 40% near the base of the unit, 60 to 70% from about the 15 to 17m level, and 25 to 40% in the upper 30m of section. Thin section observation indicates that the clasts have a composition between andesite and basalt. About 90% of the clasts are dark gray and fine-grained, the remainder are vesicular and gray. Some of the clasts with an aphanitic groundmass contain
Figure 35. Columnar Section s-d. See Plate III for traverse route.
MUDSTONE, SANDSTONE AND BRECCIA (interbedded). Mudstone is red to brown, cobble bearing, silt to grit grained, angular, very poorly sorted, moderately indurated, with good porosity, beds 15cm to 3m thick. Sandstone and conglomerate matrix, light brown, cobble bearing, fine to coarse grained, angular, very poorly sorted, moderately well indurated, massive, sandstone is more resistant than mudstone. Conglomerate clasts are locally derived brown sandstone.

UNCONSOLIDATED SAND; white to light gray, cobble and fossil pelecypod and gastropod bearing, fine to medium grained, subangular, moderately well sorted, nonindurated, massive, some "protoconcretions" of loosely consolidated sand are scattered throughout the deposit, calcite has weakly cemented the grains, average size of the concretions is from 3cm to 10cm diameter.

UNCONFORMITY.

BRECCIA; Groundmass is mudstone, brown, calcite bearing, silt to coarse grained, angular, very poorly sorted, poorly to moderately indurated, low porosity, massive, some slump blocks up to 3m across and contorted beds. Clasts are all sandstone, 2cm to 50cm diameter (3cm to 15cm clasts predominate), brown, calcite bearing, fine to coarse grained, angular, well indurated, clasts are noticeably more resistant than groundmass, deposition was probably as a mudflow.

Figure 35 continued
secondary crystals of pyrite and epidote. In most of
the vesicular clasts quartz has filled the 0.5 to 3mm
diameter gas vesicles. Thin sections of selected
nonvesicular clasts show a finely crystalline groundmass
of plagioclase crystals less than 0.1mm long. Larger
phenocrysts of plagioclase 0.2 to 1.5mm long comprise
10% of the rocks examined. Most of these grains have
slightly undulatory extinction. Epidote has replaced
parts of nearly all plagioclase phenocrysts and about
10% of the plagioclase laths have been totally replaced
by epidote. The groundmass is extensively altered to
a green clayey material, possibly chlorite. The
vesicular basaltic andesite clasts are unaltered to
only slightly altered in this fashion. Vesicles, which
constitute 10% of the thin section samples, are filled
by crystalline quartz that has grown inward from the
outer walls of the vesicles.

No sedimentary structures are evident in these
unit s-5 rocks, except for a hint of bedding given by a
1.5m thick zone at the 15m level of columnar section
s-d. In this layer the proportions of clasts is higher
than in the surrounding breccia.

The Seal Cove outcrops of unit s-5 on the west
side of the island are most assuredly lateral equiva-
lents of the volcanic breccia of Puerto Cueva Cove
based on stratigraphic position of overlying beds, the general similarity of rock type, and the agreement with an inferred projection of unit s-5 rocks through the island. Here, unit s-5 beds are located in the lower part of a southwest-facing cliff at the north end of the cove (Fig. 36), and form a dip slope on the east side of the cove. Unit s-4, however, does not crop out on the west side of the island. This relationship points to a highly lenticular nature for unit s-4 and/or unit s-5, but does not rule out the possibility of hidden or undetected faults in the central fault block.

As with the rocks of similar stratigraphic position at Puerto Cueva Cove, the Seal Cove exposures of unit s-5 show some slight bedding.

On the east side of Seal Cove where rocks of unit s-4 would be expected to crop out, a volcaniclastic conglomerate somewhat unlike that of the breccia near Puerto Cueva crops out. This conglomerate is included in unit s-5 and is assumed to pinch out laterally under the main fault block to the north. A northward projection would place it stratigraphically under the less resistant main body of unit s-5 breccia, but rock fall debris covers the contact zone at the north end of the cove. Approximately 10m this volcanic conglomerate is subaerially exposed on the east side of Seal Cove. The
Figure 36. Volcaniclastic Breccia of Unit s-5 at North End of Seal Cove. View is to the northwest.

Figure 37. Sandstone Slump Block in Unit s-5 at North End of Seal Cove. View is to the east.
Figure 36. Volcaniclastic Breccia of Unit s-5 at North End of Seal Cove. View is to the northwest.
Figure 37. Sandstone Slump Block in Unit s-5 at North End of Seal Cove. View is to the east.
rock is 40% rounded to subangular clasts and 60% immature, sandy, and largely volcanically derived mudstone matrix. This matrix is light brown, fine- to grit-grained, angular, very poorly sorted, and very well-indurated. The finer matrix particles may be altered tuffaceous material. Clasts are 95% slightly altered andesitic rocks that are light greenish brown to dark reddish gray and have a very hard, aphanitic groundmass. The remaining 5% of the clasts include brown, well-indurated sandstone, basalt, epidote-rich volcanic rock, chlorite schist, and chlorite-actinolite schist. Faint traces of west-dipping bedding planes are observed in the matrix of this breccia, and the surface of much of the outcrop slopes westward.

The main body of volcanic breccia at the north end of Seal Cove, although nearly identical in thickness and matrix-clast lithology to the Puerto Cueva outcrop, attests to some lateral variation in unit s-5. Unlike the Puerto Cueva Cove exposures, Seal Cove unit s-5 rocks have some Catalina Schist clasts, and contain large sandstone slump blocks. The matrix is a dark yellowish brown volcaniclastic mudstone. These deposits average around 30% volcanic clasts by volume. A few nonvolcanic boulders of chlorite schist and amphibole schist, believed to be of the Catalina Schist
Suite, were located near the bottom of the unit. Volcanic clasts are of andesitic basalt composition, angular, and are pebble to boulder sized. At least ten exotic slump blocks 1 to 15m long are exposed on the southwest-facing breccia outcrop. The largest block, located near the shoreline, is 15m long and is composed of fine-grained sandstone 6m in total thickness (Fig. 37). Bedding in the block is 1 to 30cm thick and regular except near the margins where the block was contorted during transport. The block strikes north-south and has rotated to dip 45°W, or about 10° steeper in westward dip than the surrounding breccia. Other, smaller slump blocks, many of which could not be closely observed are scattered throughout the unit and appear to be composed of sandstone similar to this large block.

No fossils of diagnostic sedimentary structures were observed in unit s-5. The unit is probably a marine deposit since siltstone beds directly overlying the unit contain Foraminifera. At the time of unit s-5 deposition volcanism was obviously prevalent in the source area. The sandy conglomeratic deposits typical of unit s-4 were completely overshadowed by the abrupt influx of muddy, volcanically derived breccia. The unsorted chaotic nature of the breccia and its high
degree of lateral variability suggest a submarine mudflow deposition for these rocks. That a steep paleoslope existed at the time of deposition is implied by the presence of boulder-sized volcanic clasts as well as the large sandstone slump blocks. The few Catalina Schist clasts found near the base of the unit mark the highest stratigraphic occurrence of these rocks in the strata of South Island. The source area for Catalina Schist rocks (and reworked Poway and Peninsular Range clasts as well) was either cut off and/or beveled enough to prevent clasts from reaching the Coronados area, or the abundance of volcanic debris masked the source area(s) for these rocks.

Unit S-6

Strata designated unit s-6 are the highest stratigraphic deposits of the Coronado Islands except for the terrace deposits on the east side of South Island, unit s-6 accounts for much of the topographically high but structurally down-dropped central fault block of the island. The unit consists of 140m of siltstone, breccia, sandstone, and tuffaceous sandstone that lie conformably above unit s-5. Much of the unit is masked from direct observation by terrace deposits, soil cover, and vegetation, but fresh outcrops are
located at the southwest end of Puerto Cueva Cove, and from the north end of Seal Cove to the crest of Middle Peak.

The contact with underlying unit s-5 is abrupt and irregular (Fig. 38). No angular disparity is noted between the two west-dipping units, hence, the wavy contact was probably caused by an initial bumpy surface on the last unit s-5 mudflow or by current scouring action before unit s-6 was deposited.

The lowest beds in unit s-6 are 33 to 45m of bedded sandy siltstone and fine-grained sandstone. The northern outcrop of these strata is on a northeast-facing cliff at the southwest end of Puerto Cueva Cove, where 33m of well-indurated brown to light greenish brown sandy siltstone crops out. Individual beds are 1mm to 30cm thick and have very sharp, regular bedding contacts. Thin sections of this rock show an average of 70% silty matrix and 30% sand grains. The sand fraction is primarily 0.07 to 0.15mm diameter quartz and plagioclase grains, in the proportions 70% quartz and 30% plagioclase. Small fractures in the rock are lined with iron oxide stain, but this red coloring is not extensive in the rock. Calcite is finely disseminated throughout the rock and in some cases in concentrated near microfractures.
Figure 38. Unit s-5, s-6 Contact at North End of Seal Cove. View is to the east.

Figure 39. Bedded Siltstone and Sandstone of Unit s-6 (above contact) and Underlying Volcaniclastic Breccia of Unit s-5 at North End of Seal Cove. View is to the northeast.
Figure 38. Unit s-5, s-6 Contact at North End of Seal Cove. View is to the east.
Figure 39. Bedded Siltstone and Sandstone of Unit s-6 (above contact) and Underlying Volcaniclastic Breccia of Unit s-5 at North End of Seal Cove. View is to the northeast.
A lateral equivalent of this siltstone crops out on a cliff at the northeast end of Seal Cove (Figs. 39 and 40). At this locality the rocks are interbedded sandstone and sandy siltstone in a section about 45m thick. The sandstone is light brown, mica-bearing, very fine-grained, well-sorted and well-indurated. The siltstone is similar to that of the Puerto Cueva outcrops. Bedding in the sandstone ranges from 1mm to 0.5m thick, and siltstone beds are 1mm to 10cm thick. At the 18m level in these beds a dark brown breccia lens 30m long and 3m thick crops out. The steep cliff precludes any direct observation of the lens, but it appears to have angular clasts of sedimentary and weathered volcanic rock averaging 10cm across. A breccia with similar gross characteristics that is accessible overlies the exposed siltstone beds at Puerto Cueva Cove. Here, the breccia is 16m thick, but is capped unconformably by terrace deposits of unit st-2. The breccia matrix at this locality is brown, calcite-bearing, very fine- to coarse-grained, poorly sorted, and well-indurated. Clasts include angular, brown, fine- to medium-grained sandstone and angular to sub-angular badly weathered andesite. Most clasts are 3 to 15cm diameter, but a few are 0.5m across. There are lenticular beds of similar breccia material within the
BRECCIA: Inaccessible, most likely similar to breccia above, breccia lens is 3m maximum thickness and about 30m long.

SILTSTONE: Light brown, mica bearing, well sorted, well indurated, moderate porosity, beds 1mm to 50cm thick (beds 2cm to 10cm prevail), some fine grained sandstone interbeds 3cm to 50cm thick, very sharp bedding contacts, thicker sandstone beds are laterally continuous for up to 80m.

VOLCANICLASTIC BRECCIA: Matrix is a mudstone, dark yellowish brown, silt to coarse grained, angular, very poorly sorted, moderately indurated, low porosity, massive, clasts, at least 98% of clasts are basalt, gray to black, 3cm to 50cm diameter, angular, other clasts include chlorite schist and amphibole schist, clasts constitute about 10% of the section between the 15m and 6cm level.

SANDSTONE SLUMP BLOCKS: Brown, mica bearing, fine to medium grained, moderately well sorted, angular, well indurated, low porosity, beds 1cm to 30cm thick, beds contorted near contacts with volcaniclastic breccia, not all blocks are accessible, size of slump blocks ranges from 50cm to 2m on the average, one block is 1.5m across.

Contact is concealed by talus.

VOLCANICLASTIC BRECCIA: Matrix: sandy mudstone, light brown, silt to grit grained, angular, very poorly sorted, very well indurated, very low porosity, massive except for a few nearly indistinguishable beds about 10cm thick, as a whole this breccia is more resistant than the volcanic breccia above the 1.5m level. Clasts; nearly all clasts are basalt, light greenish brown to dark redish gray, finely crystalline, angular, very resistant, average clast size is 10cm to 20cm diameter, but a few are up to 10cm across, clasts constitute about 40% of the breccia outcrops, minor clast types include epidote-rich basalt, brown, well indurated sandstone, chlorite-actinolite schist, and amphibole schist.

Sandstone of this section is feldspathic volcanic-arenite. The classification scheme of Folk (1958) is used.

Figure 40. Columnar Section s-e. See Plate III for traverse route.
SANDSTONE AND TUFFACEOUS SHALE, (interbedded): Sandstone, light brown, fine to medium grained, angular, moderately well sorted, well indurated, low porosity, beds 1cm to 2m thick (20cm to 50cm thick-beds are most common), Tuffaceous shale, light brown to greenish brown, well indurated, low porosity, beds 1cm to 6cm thick.

Rocks of 155m to 165m level are similar to sandstone, shale and tuff beds described below.

SANDSTONE, SHALE AND TUFF, (interbedded): Sandstone and shale are similar to beds described below except for increasing percentage (up to 90%) of sandstone. Tuff beds are interbedded and occur in beds 1cm to 2cm thick.

SANDSTONE: brown, tuffaceous, fine to medium grained, well sorted, very well indurated, low porosity, beds 1cm to 1cm thick.

SANDSTONE AND SHALE: similar to sandstone and shale described below.

SANDSTONE: greenish brown, mica and fossil wood chip bearing, fine to medium grained, subangular, moderately well sorted, well indurated, low porosity, beds 1cm to 2cm thick, these sandstone beds are collectively in thick and extend in outcrop for over 30m laterally.

SANDSTONE AND SHALE: similar to sandstone and shale described below, approximately 60% sandstone and 40% shale.

SHALE AND SANDSTONE, (interbedded): Approximately 50% shale and 50% sandstone. Shale, brown, clay, mica and calcite bearing, moderately well sorted, well indurated, low porosity, beds 1cm to 1cm thick, fissile, extremely fissile on weathered surface, clastic, light brown, calcite and mica bearing, fine to medium grained, subangular, moderately well sorted, very well indurated, low porosity, beds 1cm to 2cm thick, some beds 2cm to 3cm thick are continuous laterally for over 30m, some small scale cross beds, ripple marks and load casts showing no particular paleocurrent or slope directions are located in fine grained sandstone beds.

BRECCIA: similar to breccia described below, contains a slump block of andesite 3m in diameter.

SANDSTONE AND SILTSTONE, (interbedded), Sandstone, light brown, fine grained, well sorted, well indurated, low porosity, beds 2cm to 3cm thick. Siltstone, brown, well indurated, beds 1cm to 6cm thick, siltstone interbeds constitute 30% to 50% of the outcrop.

BRECCIA: matrix is mudstone, brown, fine to grit grained, angular, very poorly sorted, moderately indurated, moderate porosity, massive, outcrop is wedge shaped, over a 7cm outcrop thickness is from 3m at one end to 1cm at the west end of the outcrop, matrix makes up 50% of the bed, sharp contacts with adjacent beds above and below. Clasts are 30% basaltic and badly weathered andesite and 10% brown well indurated sandstone, clasts are 3cm to 30cm diameter, angular to subangular.

SILTSTONE: similar to siltstone below, dark brown to gray, possibly finer grained than siltstone below.

Figure 40 continued
outcrop that may be slump features or channel fillings. Unit st-2 rocks unconformably cap the breccia at this locality and only a few outcrops of unit s-6 breccia and sandstone higher in the section crop out on the soil-covered east slope of Middle Peak. These two breccia outcrops on opposite sides of the island are probably not continuous with one another, but more than likely represent similar penecontemporaneous depositional conditions.

Unlike the east side of the island, a completely exposed section of unit s-6 crops out in the Seal Cove-Middle Peak area (Fig. 40). As previously mentioned, the lower 20m of unit s-6 at Seal Cove is interbedded sandstone and siltstone plus a lenticular breccia deposit. About 30m of bedded sandstone and siltstone similar to the lower unit s-6 rocks overlie the breccia lens. These fine-grained rocks are in turn overlain by another breccia layer. The thickness of this particular breccia varies from 5m due south of Middle Peak to 12m at its point of termination by the east-dipping fault just north of the small peninsula at Seal Cove. Matrix material in this bed is a brown, fine- to grit-grained, poorly sorted, moderately indurated, massive mudstone. Angular to subangular clasts with diameters of 3 to 30cm make up about 40% of
the deposit. Clast types are 90% moderately fresh to badly weathered andesite and 10% brown, well-indurated sandstone. Contacts with sandy beds above and below this breccia are very sharp and only slightly irregular. The overlying and underlying fine-grained sandstone beds are subparallel to the upper and lower limits of the breccia wedge respectively. This accounts for the angular disparity between strata above and below the breccia. The lower beds strike N20°E and dip 35°W. Beds above the breccia strike N40°E and dip 35°W. This attitude difference in the strata above and below was most likely caused by the breccia being laid down as a wedge-shaped deposit. The rocks above the breccia are light brown, fine-grained sandstone with 20 to 30% siltstone interbeds. Sandstone beds are 2 to 30cm thick, siltstone interbeds are predominantly 10cm thick. Similar rocks are present up section for about 12m where silty beds become more fissile and sandstone beds make up about 60% of the section. This interbedded sandstone and shale sequence is evident in the section s-e traverse (Fig. 40) from the bottom of a gulch near the major fault northwest of Seal Cove to a level 48m stratigraphically higher, about 30m below the crest of Middle Peak (Plate III). Sandstone beds in this sequence are light brown, fine- to medium-grained, moderately
well-sorted, well-indurated, locally calcitically cemented and finely bedded. Some sandstone beds are clayey and/or tuffaceous. Individual beds are a few millimeters to 40mm thick. Shale beds are brown to green, mica-bearing, well-indurated and form beds 1mm to 1cm thick. Sections of exclusive shale beds are about 10cm to 2m thick, however, sandstone interbeds a few centimeters to 1m thick are commonly present at 20cm to 1m intervals. These beds are about 60% sandstone and 40% shale by volume.

The stratigraphically highest occurrence of mudflow breccia in unit s-6 is within this sequence (Fig. 40). Thickness of the breccia is 3 to 5m at the only accessible locality on a knoll overlooking Seal Cove. Here, the matrix and general clast types are similar to the lower breccia beds. An exception is the presence of a clast of blocky andesite 3m across. This is the largest single volcanic clast found anywhere on South Island. The surrounding sandstone and shale beds are in great contrast to this breccia bed in clast size, lithology and bedding. Above the breccia bed is a section of rhythmically bedded fine- to medium-grained sandstone and shale (Figs. 40 and 41). Sandstone and shale are evenly distributed by volume up section to the 135m stratigraphic level of section s-e where
Figure 41. Interbedded Sandstone and Shale of Unit s-6 West of Middle Peak. View is to the east.
Figure 41. Interbedded Sandstone and Shale of Unit s-6 West of Middle Peak. View is to the east.
sandstone becomes the dominant rock type. At the 165m level of section s-e sandstone beds make up 90 to 95% of the section with the remainder being 5 to 10% finely bedded tuffaceous shale interbeds. There is also a greater frequency of sandstone beds in the 20cm to 2m range of thickness. The sandstone beds are tuffaceous feldspathic volcanic arenites as determined by thin section study. Proportions of grain types are quartz 25%, feldspar 25%, and rock fragments (nearly all of which are volcanic) 50%. Minor constituents present in the rock are mica flakes, interstitial calcite, various opaque minerals, pyroxene and epidote grains, and hematitic stain. Ten to 15% of the sandstone is a matrix derived largely from decomposed volcanic rock fragments. Mica flakes and some volcanic rock fragments are crushed, indicating post-depositional compaction. These beds form the crest of Middle Peak and are the highest stratigraphic outcrops of Miocene beds on South Island.

The lower part of unit s-6 has sedimentary structures indicative of a northeast current direction. The siltstone on the northeast-facing cliff at the south end of Puerto Cueva Cove (70m level of section s-d, Fig. 35, p. 111) contains groove casts oriented in a N65°E to N70°E (or S65°W to S70°W) direction.
These casts are 5mm wide and at least 30cm long. In the same beds, 3m below the lowest breccia bed, asymmetric ripple marks with wavelengths of 1cm indicate a current direction of \( N10^\circ E \) to \( N15^\circ E \). The breccia that overlies these siltstone beds shows evidence of channel filling and slumping of sediment, but no slope/current directions were ascertained. The ripple marks and groove casts are the only definitive directional structures in unit s-6, however, the few readings obtained coincide with a general north to northeast current and down-slope direction during deposition of units s-1, s-2, and s-3.

The siltstone of unit s-6 at Puerto Cueva Cove contains microscopic fish teeth, fragments of wood, and foraminifera dated as middle Miocene. Six bulk samples of fine-grained rocks recovered throughout the section of unit s-6 rocks north of Seal Cove contain scattered wood chips up to 3cm wide, 0.5mm thick and 20cm long, but proved to be barren of microfossils.

The bulk of unit s-6 reflects rather quiet, low energy, current-born deposition of thin silt, and fine- to medium-grained sandstone layers. These marine deposits were laid down on a steep paleoslope of undetermined attitude, but current directions were north to northeast at least during deposition of the lower
30m of the unit. As with other South Island deposits, unit s-6 was heavily influenced by a volcanic source area. Quiet, fine-grained deposition was periodically interrupted by rapid influxes of muddy volcaniclastic breccia flows that formed lenticular or wedge-shaped beds. The few large volcanic clasts from 0.5 to 3m diameter located in these breccia beds suggests a primarily volcanic source area of at least moderate relief. Fossil wood fragments indicate a terrestrial source area was within a few tens of kilometers at the time of deposition.

**Unit St-1 and St-2**

Two distinct Pleistocene deposits crop out on South Island. The smallest of the two (unit st-1) is a small remnant of a shingle beach perched 55m above sea level just west of the landslide debris south of north lighthouse. The other is a remnant of a beach and terrace located at the south end of Puerto Cueva Cove at an elevation of 30m above sea level. The deposits probably represent different sea level stands in Pleistocene time, but the ages of the units relative to each other is unknown.

Directly south of north lighthouse and just west of the landslide debris, a small outcrop of
gravelly beach deposits (unit st-1) is perched on a sandstone outcrop adjacent to and east of the main fault through the area (Fig. 42). The outcrop is the eroded remnant of a larger deposit. There is no lithologic or structural connection between this outcrop and those of unit st-2 near Puerto Cueva Cove. Unit st-1 is located on a small east-sloping wave-cut terrace at an approximate elevation of 55m. The outcrop is 3m wide, 7m long, and 1.5m thick and consists entirely of poorly indurated conglomerate with a reddish brown sandy matrix. Most clasts are beach-worn, that is, they have smooth surfaces, are rounded to well rounded, and are highly oblate with long dimensions that are two to three times as great as their thicknesses. The average size of clasts in this conglomerate is 3 to 8cm in long diameter, though a few clasts 0.5m in diameter are present. These clasts appear to be locally derived, but do not represent the complete lithologic assemblage of the underlying Miocene conglomerate. A high percentage of these clasts are very resistant rocks such as rhyolite, andesite, quartzite, vein quartz, quartz-amphibole schist, and well-indurated sandstone. The groundmass is reddish brown, pebble-bearing, medium- to coarse-grained, angular, poorly sorted, moderately indurated
Figure 42. Unit st-1 Terrace Deposit on East Side of South Island. View is to the south.

Figure 43. South End of Puerto Cueva Cove. Note Unit st-2 Terrace Deposits above West-dipping Miocene Rocks. View is to the southwest.
Figure 42. Unit st-1 Terrace Deposit on East Side of South Island. View is to the south.
Figure 43. South End of Puerto Cueva Cove. Note Unit st-2 Terrace Deposits above West-dipping Miocene Rocks. View is to the southwest.
and massive.

A 4m wide gulch in the adjacent fault zone borders the conglomerate to the west. On the south side of this gulch, next to, and about 2m topographically below the conglomerate is an outcrop of similar sandstone and conglomerate 0.5m thick and 5m long. Wave action must have eroded the fault zone before deposition and the coarse clastic debris was deposited in the resulting channel.

The present-day pebble and cobble beach at Seal Cove is nearly identical (except for the reddish brown matrix) to the conglomerates of unit st-1. The Seal Cove beach clasts are rounded to well rounded, oblate, and similarly consist of the more resistant clasts derived from South Island Miocene rocks. This similarity suggests that clasts and sand of unit st-1 were tumbled by wave action on a small pocket beach.

The northern terrace exposure (unit st-2) unconformably overlies the west-dipping units s-4, s-5, and s-6 on the northeast-facing cliff at the south end of Puerto Cueva Cove (Fig. 43). This unconformable contact is sharp on the cliff face, but elsewhere it can only be inferred due to soil cover (Plate III). The unit strikes N30°W and dips northeast 10°. This slightly tilted attitude most likely developed at the
time of deposition. The surface topography has a similar attitude, yet these rocks form the flattest part of the island.

The lowest outcrop of unit st-2 is unconsolidated sand of a beach or shallow subtidal deposit that crops out 30m above sea level only at the northwest end of the unit st-2 exposure west of the south end of Puerto Cueva Cove. These sandy deposits formed at or near a pocket beach that apparently developed along the existing fault between rocks of units s-3 and s-6. A similar pocket beach along the same fault now exists at the extreme southwest corner of Puerto Cueva Cove. The sand is found in discontinuous exposures for more than 10m on the steep slope of the island, but much of this sand is float material and the actual in situ deposit may be less than 10m thick. At the extreme west end of the cliff at the south end of Puerto Cueva Cove the sand deposits unconformably overlie breccia deposits of unit s-6, but pinch out a few meters to the east. The exposed sand strongly resembles a modern beach or shallow subtidal deposit. It is white, fine- to medium-grained, and moderately well-sorted. The only indication of lithification is scattered poorly indurated calcium carbonate-rich "proto concretions" 3 to 10cm in diameter. Rounded, beach-worn
cobbles and boulders of quartz-rich rock and metavolcanic rock 5 to 30 cm diameter are interspersed at random in the sand. Numerous fragments and a few whole specimens of pelecypods and gastropods are present, and a few large cobbles have intertidal carbonate fossil remains attached to their surfaces. Although no detailed analysis has yet been done on these fossils, preliminary examination by several paleontologists yielded estimations of a probable Pleistocene age.

This sandy deposit is almost entirely covered by scree from higher deposits, hence, vertical and lateral tracing of the sand is difficult. It appears as though the deposit is lenticular in shape, although the upper contact with overlying terrace parts of unit st-2 is nearly horizontal. The sand was probably deposited on an irregular surface at the bottom of a cove.

Mudstone, breccia and sandstone terrace deposits overlie the sand at the western limits of the unit st-2 outcrop, and these deposits lie directly on the westward-dipping rocks of units s-4, s-5 and s-6 a few tens of meters to the east. About 12 m of these terrace deposits are exposed on the upper portions of the cliff at the south end of Puerto Cueva Cove (Fig. 43). This section is predominantly pebble- and
cobble-bearing mudstone with interbeds of breccia and sandstone. The mudstone is red to brown, has angular, fine- to grit-sized grains and is very poorly sorted and moderately well-indurated. Beds are internally massive and range in thickness from 10cm to 2m. Clasts in the mudstone and breccia are angular blocks of sandstone 5cm to 0.5m diameter. These angular rocks appear to be derived locally from the adjacent unit s-6 sandstone that comprises a good portion of Middle Peak. Sandstone interbeds are slightly more resistant than the mudstone and breccia beds and form overhangs on the cliff face. The sandstone is light brown to reddish brown, fine- to coarse-grained, very poorly sorted, angular, and moderately well-indurated with a silty matrix. Beds are 10 to 30cm thick.

The trace of the unconformity between unit st-2 and underlying Miocene rocks is nearly horizontal when viewed from Puerto Cueva Cove (Fig. 43), though the hidden erosion surface of the unconformity may slope northeast a few degrees. This surface is a wave-cut terrace upon which the deposits of unit st-2 were laid down. Wave action probably eroded deeper along the fault zone west of the cove and allowed for the subsequent deposition of beach sand in the trough. The mudstone, breccia and sandstone portions of unit st-2
were then deposited on the wave-cut terrace and over the beach sand deposits. Source material for these sediments was local, yielding a large percentage of volcanic rock fragments. Decomposition of these grains accounts for the red color of the unit st-2 terrace deposits. Whether or not this oxidation occurred penecontemporaneously with deposition is not known. In any case, the fine-grained st-2 deposits were probably placed by current or wave action and the breccia layers were laid down as terrestrial or shallow subtidal mudflows.

Unit Ls

The unit Ls landslide debris is located along the east side of the island south of north lighthouse. Here, the combination of oversteepening by wave action to the east and the presence of a weak (fault) zone near the crest of the island caused a portion of unit s-2 to slide. A vertical cliff when the parting took place remains on the southwest side of the landslide. The fallen debris has partially slid into the sea creating a bulge in the shoreline. Vegetation presently covers much of the debris, though the slide could easily have occurred in historic times. The slide is composed almost entirely of fractured blocks of unit s-2.
Geologic Structure

The most obvious geologic structures of South Island are its homoclinal, westward-dipping strata and the northeast-trending normal faults. With the exception of the terrace deposits of units st-1 and st-2, and local variances caused by drag folding, the rocks of South Island dip 12 to 35°W and strike N25°E to N25°W. Folding is limited to drag near faults. Joints are absent or not apparent at the surface in most South Island rocks except in the top of unit s-4.

A dominant structural feature of the island is the down dropped, though topographically high, block in the north-central part of the island. This graben is bordered by two northeast-trending normal faults.

The fault forming the western border of the block strikes N15°E to N20°E and dips 35 to 42°E, causing an arcuate trace over the surface of the island. Slickensides were not located on exposed surfaces of this fault, but drag folding in unit s-6 rocks of the graben (Fig. 44) indicate the major component of latest movement on the fault was down dip. At least 150 to 200m of stratigraphic displacement has taken place along this fault between unit s-3 west of the graben and units s-4, s-5, and s-6 in the graben. Estimated stratigraphic displacements on this and other
Figure 44. Main Fault on West Side of Central Fault Block, West of Seal Cove. Unit s-3 is to the left and unit s-6 is to right of fault. View is to the north.
Figure 44. Main Fault on West Side of Central Fault Block, West of Seal Cove. Unit s-3 is to the left and unit s-6 is to right of fault. View is to the north.
faults of the island are based on measured thicknesses of subaerial rock units, and only a minimum displacement is indicated. Two secondary faults in unit s-6 siltstone at the southwest end of Puerto Cueva Cove lie parallel to, and 2 and 6m respectively above, this main fault. The lower of these faults strikes N20°E, dips 35°E, and shows no slickensides, but does exhibit a normal displacement of 10m. The higher fault strikes N30°E, dips 45°E, shows about 5m of normal displacement, and has slickensides which are parallel to the dip of the fault plane. The main fault zone at this locality makes a very sharp contact between unit s-3 rocks on the west and the graben on the east. Aside from minor fracturing, the better indurated rocks of unit s-3 are relatively unaffected by the faulting as close as a few centimeters from the main fault plane. Conversely, unit s-5 and s-6 are brecciated in a zone 1 to 2m wide, and have developed drag folds as well as contorted beds adjacent to and up to 6m away from the major fault break. Volcanic breccia of unit s-5, where it is in contact with unit s-3 along this fault, is extensively fractured and partially chloritized in a zone 1.5m wide. At sea level, wave action has differentially eroded this fracture zone and produced a sea cave, the roof of which has partially fallen.
The fault at the eastern edge of the central fault block has a relatively straight trace over the island due to an average fault surface strike of N15°E and a dip of 80 to 85°W. The latest episode of movement on this fault was normal as shown by drag folding in unit s-6 rocks near Seal Cove (Fig. 45) and by slickensides parallel to the dip in the same general area. An estimated 250 to 300m of stratigraphic displacement has occurred on this fault. Unlike the fault at the west edge of the graben, where secondary faults are detached and subparallel to the main fault, the present fault displays several lateral faults that branch from the major fault zone. One fault slice between the major zone and a north-trending fault branch near Seal Cove contains rocks of unit s-6 that have down-dropped below the bulk of the unit s-6 rocks in the graben (Fig. 45). Between the landslide area and North Lighthouse the main fault is difficult to detect since rocks of similar lithology (units s-3 and s-4) lie on both sides. There are many related faults in this area that are partially masked by landslide material, soil, and vegetation. Relative to the middle and southern parts of this main fault, a greater percentage of movement in the northern area has been taken up by several faults as opposed to one zone of
Figure 45. Main Fault on East Side of Central Fault Block, East of Seal Cove. Down-dropped unit s-6 beds are to left, and unit s-2 rocks are to the right of fault. View is to the northeast.
large displacement.

The down-dropped block itself contains numerous faults of smaller displacement. Where determinable the sense of slip on these faults is normal. Three eastward-dipping normal faults with less than 2m of dip slip are evident on the southwest-facing cliff at the north end of Seal Cove. Other minor faults in the block are located at the south end of Puerto Cueva Cove, and on the peninsula east of the cove.

With the exception of two east-west faults near Puerto Cueva Cove, the north part of the island is cut only by northeast-trending normal faults. One fault, separating unit s-1 and s-2 rocks from unit s-3 strata in the north part of the island has 250 to 300m of stratigraphic displacement. This fault strikes N30°E and dips 50 to 65°E. Relatively little disruption of adjacent strata has taken place along the fault zone. Slickensides were not located along this fault, but smaller nearby faults commonly have 3 to 10m of normal displacement, and a few exhibit slickensides subparallel to the dip of the fault zone.

The north end of the island has four nearly parallel faults striking N35°E and dipping 35 to 40°SE. Normal displacement of about 15m is evident on two of the faults. Again, the fault traces are sharp where
exposed on fresh outcrops and only slight bedding disruption has taken place along the fractures.

Two east-west faults cut unit s-3 rocks west of Puerto Cueva Cove. These faults are nearly vertical and the sense of movement along them has not been determined, however, it is suspected that rocks on the southern side of each fault have been down-dropped relative to those on the north.

The southern two-thirds of South Island is free of major faults and about half of the minor fractures located trend northwest rather than northeast. The major northwest-striking trends of Middle Island could, by projection to the south, intersect rocks just west of the southern part of South Island. In general, faults in this southern block are difficult to locate because of inaccessibility, the resistant, nearly homogeneous rock, vegetation, and soil cover. Only where wave action has differentially eroded fault zones are they readily apparent. Hence, it is likely that more faults than those mapped are present in the southern block of the island. A small northeast-striking fault west of South Peak is the only one of these minor faults where a sense of movement was determined. This fault strikes N10°E, dips 80°W, and has a massively slickensided surface showing evidence
of dip slip movement.

**Age of South Island Rocks**

Woodford (1925) proposed a Miocene age for South Island rocks on the basis of their lithologic similarity to the Miocene San Onofre Breccia near Oceanside, California. At both localities Catalina Schist-type clasts are incorporated in conglomerate and breccia beds. Later study by Emery and others (1952) confirmed Woodford's original age estimation by the discovery of middle Miocene Foraminifera in the fine-grained rocks from the northeast part of the island (units s-1, and s-3 of this report). Concerning these fossils, Emery and others reported as follows:

They consist entirely of limonitic internal casts, possibly originally of pyrite. Dr. Orville Bandy, of the University of Southern California, identified the following forms: *Bolivina marginata* Cushman, *Buliminilla subfusiformis* Cushman, *Nonion costuferus* (Cushman), *Nonionella miocenica* Cushman, (?) *Siphogenerina* sp. (partial internal mold), *Valvulineria cf. miocenica* Cushman. These Foraminifera are characteristic of the middle Miocene, supporting the lithologic correlation of the overlying and probably also underlying green conglomerate with the San Onofre Breccia. (p. 523)

In 1969 R. G. Gastil of San Diego State University collected samples from units s-3 and s-6 of the present report which were analyzed by Texaco laboratories. Texaco paleontologists characterized the
fossils, collected on the west side of Puerto Cueva Cove (unit s-3), as definitely middle Miocene and probably Relisian in age. They noted a strong resemblance to the Topanga Sequence in the southeast Los Angeles Basin. These determinations were supported by middle Miocene nanoplanckton as well. The sample collected by Gastil from the siltstone beds at the south end of Puerto Cueva Cove (unit s-6) contained no nanoplanckton, and only a few limonitic casts of some calcareous Foraminifera that are representative but not indicative of Miocene rocks of California. This same sample contained abundant arenaceous fauna which were unfamiliar to the Texaco personnel in terms of California species. However, some affinities were noted in these arenaceous forms to Eocene-Paleocene-Cretaceous types. They also believed it possible that the arenaceous fauna were a Miocene assemblage that they had not seen before.

Several bulk samples of fine-grained rocks were collected during the present study, and analyzed for microfossils by Mobil Oil Company laboratories. Foraminifera were recovered from siltstone and shale of unit s-1 along the columnar section s-a traverse route. The narrowest range given any one sample was Saucesian to Lower Luisian of the Miocene. Fossils
found in these unit s-1 rocks included AmOdiscus sp., Bulimina sp., Haplophragmoides spp., Globigerina cf. Bulloides, Trochammina sp., Uvigerina sp., Valvulinaria cg., and Virgulina sp. Arenaceous species are the most abundant forms present. All calcareous forms were reported to be limonite casts as similarly reported by Emery and others (1952).

A unit s-3 sample collected from the siltstone 5m above the conglomeratic beds in the small fault slice directly across the cove and west of the tip of north lighthouse peninsula proved to be of Saucesian to Lower Mohnian age. Again all calcareous Foraminifera were replaced by limonite and arenaceous forms were abundant. This fauna consisted of Bulimina sp., Haplophragmoides spp., Nonion cf. costiferum, Nonionella miocenica, Phabdamina sp., Trochammina sp., and Virgulina sp.

The siltstone of lower unit s-6 at the south end of Puerto Cuava Cove yielded Foraminifera of probable Saucesian to Lower Luisian age. Taken as a whole, these samples contained the following fossil forms: Bolivina sp., Bulimina(?), Gavelinella sp., Haplophragmoides spp., Praebulimina venusae, and Valvulineria cf. depressa. Just as the Texaco reports indicated a possible affinity to early Tertiary forms,
Mobil paleontologists suggested the possibility of some reworked fossils being present.

Based on the data obtained in this study and in previous investigations, a middle Miocene (Saucesian to Lower Mohnian) age for units s-1 through s-6 is moderately certain.
Chapter 5

LOCAL AND REGIONAL GEOLOGICAL HISTORY;
A PERSPECTIVE

General Statement

The coastal southern California, northwestern Baja California, and the Continental Borderland region has a varied and complicated geologic history. The rock record indicates that this portion of western North America has experienced much tectonic activity from Late Mesozoic to Recent time. Employing the various theories and models of the Global Tectonics ideas (Isacks and others, 1967), it is apparent that the region has incorporated or been close to major crustal plate margins since the Middle Jurassic. According to Atwater (1970) the oceanic Farallon Plate was being subducted beneath western North America in Mesozoic and probably much of Paleogene time. The spreading center at the western margin of the Farallon Plate was migrating eastward as well (in a relative sense), approached the immediate coastal area in Miocene time (Atwater, 1970), and juxtaposed the Pacific Plate against the North American Plate. Since then a generalized east-west crustal dilation in the
Miocene and subsequent northwest-trending lateral movement between these plates has profoundly influenced the regional geologic history.

The Coronado Islands proper offer only a limited late Cretaceous, middle Miocene, and Pleistocene view of local geologic history. Since material comprising the whole island group was ultimately derived from the southern California-northwestern Baja California region, a general review of regional geologic history will be presented in this section in order to put the more detailed geologic history of the Coronado Islands in a clearer perspective. Of particular importance in describing regional geologic history relative to the Coronado Islands is the tracing of origin, uplift, and erosion of the Catalina Schist. Tectonic forces that ultimately led to the deposition of Catalina Schist clasts in the Coronados area and elsewhere on the Borderland and coastal areas will be discussed in the regional history sections of this chapter. More detailed accounts of the Coronados Islands-San Diego-Tijuana area will be presented under the local history subtitles.

Regional Mesozoic History

Among the oldest rocks exposed along the
western margin of the northern Peninsular Range are the Santiago Peak Volcanics (Larsen, 1948). Discontinuous outcrops of these and related rocks are located in a narrow zone on the western edge of the Peninsular Range batholith from Orange County, southward into Baja California. The Santiago Peak Volcanics are largely andesitic to basaltic metavolcanic flows, agglomerates, and volcanically derived sediments. Fossils of Upper Jurassic (Portlandian) age have been recovered from fine-grained metasediments interbedded with the volcanic rocks near Rancho Santa Fe north of San Diego (Fife and others, 1967). Tight folding of these metasediments is apparent in the same general area. According to Larsen (1948) deformation of the Santiago Peak Volcanics was penecontemporaneous with a mild regional metamorphism sometime before intrusion of the Cretaceous southern California batholith.

The origin of the Santiago Peak Volcanics may be analogous to presently active andesitic volcanism around the Pacific Rim (Hawkins, 1970a; Peterson and Abbott, 1973). Quaternary andesitic volcanism of the Circum Pacific belt is associated with ongoing subduction of an oceanic plate under a volcanically active island arc or continental margin. Similarly, deposition of the Santiago Peak Volcanics may have been associated
with contemporaneous subduction of oceanic crust beneath southern California some distance (about 100km according to Hawkins, 1970a) to the west. Hamilton (1969) noted that pre-Mesozoic continental rocks are present only within and east of the southern California batholith area. West of the batholith such rocks could lie under the ocean floor or be masked by post-Mesozoic sedimentation, but Hamilton (1969) proposed that,

West of the batholith, however, there probably was no continental crust present in Early Mesozoic time. The argillite section [Bedford Canyon Formation] may have been promptly incorporated tectonically into the edge of the continent. The overlying high Upper Jurassic volcanic rocks presumably are co-genetic with part of the batholith. (p. 2420)

In the same paper Hamilton described Upper Jurassic andesitic belts, similar to the Santiago Peak Volcanics, located along the western margin of the Sierra Nevada and Klammath Mountains batholiths. Hamilton determined that these belts could be remnants of island arcs or the volcanic equivalents of nearby batholithic rocks. Mesozoic andesitic rocks are not found, however, on the Salinian Block, which must be included as an intervening crustal block between southern California and the Sierra Nevadas in any pre-San Andreas reconstruction of western
California. Nevertheless, a Late Jurassic palinspastic reconstruction of California presents a narrow, but perhaps discontinuous, belt of andesitic volcanism and associated plutonic activity over 1000 km in length. In terms of plate tectonics these linear lithologic trends are best explained as landward expressions of an east-dipping subduction zone that was active in Late Jurassic time.

Mesozoic underthrusting of oceanic crust beneath the North American continent has been proposed by several authors. The more generalized works include papers by Dietz (1963), Gilluly (1963), Yeats (1968a, 1968b), Hamilton (1969), Ernst (1970), and Hill (1971). The most convincing features of this converging plate hypothesis are the narrow, linear outcrops of Mesozoic sedimentary, metamorphic, and igneous rocks along the west edge of North America. The similarity of age and lithology of the batholithic rocks alone strongly favors a subduction-related origin for these rocks (Gilluly, 1963; Hamilton, 1969; Lipman and others, 1971). In California, perhaps the most convincing evidence comes from the lithologic properties and spatial arrangement of the Great Valley Sequence, Franciscan rocks, and the Sierra Nevada, Coast Ranges, and Peninsular Ranges batholiths. The Great Valley
Sequence is a series of Upper Jurassic to Late Cretaceous shale, sandstone and conglomerate that crops out along the west edge of the Great Valley and in the Central Coast Ranges (Fig. 46). These rocks form a westward-thickening wedge that is over 40,000 ft. (12,000m) thick (Bailey and others, 1964). The Franciscan assemblage is a lithologically varied and structurally complex eugeosynclinal section that ranges in age from Upper Jurassic to Late Cretaceous. Rock types typical of the Franciscan terrane include graywacke sandstone, shale, bedded chert, altered mafic volcanic rock (often exhibiting pillow structures), metamorphic rocks of the blueschist and greenschist facies, and minor amounts of serpentine and other ultramafic rocks (Bailey and others, 1964). The Great Valley Sequence is much less tectonically deformed than the rocks of the Franciscan assemblage. Rocks of Franciscan origin were deposited on a continental rise or in a trench which was actively downwarping, whereas, the Great Valley Sequence was deposited on a shelf, perhaps as an arc-trench gap deposit. Contacts between these two coeval rock groups are apparently tectonic, and in some places are separated by thick zones of serpentine (Bailey and others, 1964). Areas where Great Valley rocks are overthrust relative to Franciscan
Figure 46. Distribution of the Great Valley Sequence and Franciscan Rocks. From Bailey and others, 1964.
rocks have been mapped in central California (Bailey and others, 1970; Ernst, 1965) and in coastal central California (Brown, 1968; Gilbert and Dickinson, 1970; Page, 1970). Underthrusting of Franciscan rocks is also documented in the Klamath Mountains (Irwin, 1964; Davis, 1968; Seyfort, 1968). Further evidence that at least parts of the Franciscan assemblage were subducted to great depths is exhibited in the various exotic blueschist and greenschist facies minerals that formed under high pressure-low temperature conditions (Ernst, 1965).

South of the Transverse Ranges evidence of the subduction of Franciscan-like rocks beneath the continent is more difficult to ascertain. There are few outcrops of these rocks in the southern California-Baja California coastal areas. Much of the continental margin is below sea level and extensive Cenozoic volcanic and sedimentary deposits blanket the area. In addition, the imprint of Mesozoic plate convergence has been grossly altered by dilational and lateral tectonics during Cenozoic time. The only subaerial outcrops of Franciscan-like rocks in southern California are on the Palos Verdes Peninsula and on Santa Catalina Island. These southern equivalents of the Franciscan are termed the Catalina metamorphic facies of the Franciscan; or
the Catalina Schist (Woodford, 1924). Dredging has revealed several areas of suspected submarine Catalina Schist outcrops on the eastern (Emery and Shepard, 1945), and western (Winterer and others, 1969) Continental Borderland (Fig. 47). Cohen and others (1963) described typical Franciscan sedimentary, metamorphic and volcanic rocks comprising the San Benito Islands 1000km south of the International Border on the west coast of Baja California. These outcrops, along with the occurrence of Catalina Schist debris in the Miocene San Onofre Breccia (Woodford, 1925) and related rocks of southern California and northwestern Baja California are a strong indication that Franciscan-Catalina Schist bedrock may be present over large areas of the continental margin (Fig. 47).

Evidence of actual subduction of Franciscan-Catalina Schist rocks is speculative, since only sparse data are available. The graywacke, chert, and diabase dredged from the outer continental shelf (Patton Escarpment) by Winterer and others (1969) contained laumontite. On the assumption that these laumontite-bearing rocks are time correlative to blueschist rocks (Catalina Schist) near Los Angeles and greenschist rocks (Pelona Schist) of the San Gabriel Mountains, Winterer and others suggested a facies progression from
Locations of subaerial Franciscan-Catalina schist outcrops

Areas of submarine Franciscan-Catalina schist outcrops (after Emery, 1960; Winterer and others, 1969)

Areas possibly underlain by Franciscan-Catalina schist bedrock (probably covered by Cenozoic rocks in most areas)

Postulated Mesozoic Southern California subduction zone of Hill (1970)

Figure 47. Distribution of Franciscan-Catalina Schist Rocks Off the Southern California-Baja California Coast.
west to east of (1) low pressure-low temperature, (2) high pressure-low temperature, to (3) moderate pressure and temperature conditions. These data expand the similar assertion of Yeats (1968a) of a north-eastward change of metamorphic facies from blueschist rocks in the Los Angeles area to greenschist rocks near localized thrust faults in the San Gabriel Mountains. Both of the above hypotheses rely on the still-tenuous correlation of Catalina Schist rocks with the Pelona Schist, but the general facies pattern is suggestive of Mesozoic subduction off southern California. Hill (1971) has proposed the name southern California subduction zone for the suspected thrust contact between Catalina Schist rocks and the granitic basement of the Peninsular Ranges (Fig. 47).

Subduction and volcanism probably continued through Cretaceous time when the bulk of the southern California batholith intruded into pre-Mesozoic metamorphic rocks and the Santiago Peak Volcanics. Hamilton and Myers (1966) hypothesize that batholiths in general, rather than forming beneath thick piles of eugeosynclinal deposits, are emplaced as relatively shallow bodies beneath a thin (less than a few kilometers) pile of their own volcanic equivalents. Assuming that subaerial erosion takes place continuously with intrusion,
crystalline rocks emplaced at these shallow depths would be exhumed in a geologically short time. This model seems applicable to the Peninsular Ranges since rocks derived from the unroofed southern California batholith are incorporated in nonmarine Upper Cretaceous conglomeratic rocks in Orange County (Trabuco Formation, Popenoe, 1941), San Diego County (the Lusardi Formation of Nordstrom, 1970), and in the Tijuana area (Redonda Formation of Flynn, 1970). Extensive erosion of the batholith preceded deposition of these rocks, as they were all deposited nonconformably on a moderate-to high-relief crystalline terrain.

Following the initial deposition of fluvial debris, the Late Cretaceous shoreline of southern California apparently transgressed to a few kilometers east of the present-day coast, and marine shelf sediments were deposited over the continental beds. Although buried by younger rocks in most localities, these Late Cretaceous marine rocks presently crop out along the western margin of the northern Peninsular Range in southern Orange County (Williams and Ladd Formations, see Morton, 1972), in small patches near Carlsbad (Bandy, 1951; Popenoe and others, 1960; Holden, 1964), along the coast from La Jolla to Point Loma (Point Loma and Cabrillo Formations of Kennedy and Moore, 1971) and
south of Rosarito Beach in Baja California (the Rosario Formation of Anonymous, 1924; Beal, 1948). These rocks are mostly shale, siltstone, and sandstone with some interbedded conglomerate. From the Late Cretaceous to Early Miocene time sedimentary rocks deposited along the western margin of the northern Peninsular Ranges formed a westward-thickening coastal wedge (Yeats, 1968a, 1968b). Yeats (1968b) recognized the difficulty in reconstructing such a model for southern California due to later deformation, but he makes a tentative correlation between these rocks and the Great Valley wedge of Hackel (1966) and the coastal wedge of Baja California (Allison, 1968). Although no equal to the Great Valley Sequence in thickness, areal extent or range of age, the southern California Cretaceous coastal wedge, like the Great Valley Sequence, may be an arc-trench gap deposit.

Yeats (1968a, 1968b) reported that thrust contacts in the San Gabriel Mountains between granitic basement and Pelona Schist rocks are overlain by Paleocene sedimentary rocks. This indicates termination of thrust faulting in the San Gabriel Mountains area before Paleocene time, but not necessarily the ceasing of subduction offshore. The plate motion model of Atwater (1970) provides for continued convergence of
the Farallon and North American plates well into Tertiary time. Andesitic volcanic activity continued in the western United States through early Tertiary time suggesting continuance of subduction along the west coast (Lipman and others, 1970, 1971). The rate at which the Farallon Plate was being consumed may have been reduced (possibly resulting in the termination of plutonic activity by Late Cretaceous time), or the main zone of subduction could have migrated farther west, thus reducing tectonic effects in the Peninsular Ranges. In any case, the stage was set for Late Cretaceous through Oligocene sedimentation and erosion along the relatively stable southern California and Baja California coastal region.

Local Mesozoic History

By Late Cretaceous time the batholith and metamorphic terrain east of the San Diego-Tijuana area had uplifted, partially eroded, and shed debris seaward. Sediment of the nonmarine Lusardi and Redonda Formations was being deposited on a basement surface of moderate to high relief. The red beds of North Island (unit n-1) are tentatively correlated as a finer-grained equivalent of the Lusardi and Redonda Formations on the basis of their nonmarine appearance, the presence
of Peninsular Range clasts and the absence of Poway Suite clasts (see Chapter 2 of this report). A seaward-sloping depositional plain extended from the batholith westward to the Coronado Islands area. The Lusardi and Redonda Formations are largely conglomeratic and were deposited by fast-moving streams and mudflows (Peterson, 1971, 1971; Nordstrom, 1970; Flynn, 1970). The North Island beds, on the other hand, are medium- to coarse-grained sandstone that reflects a quieter, deposition by relatively slower currents. It is probable that the North Island area was a freshwater-marine transition zone of slight relief where periodic flooding brought in fresh water and sand from the east. The sediment must have been exposed to the atmosphere for long periods of time to permit oxidation of the sand layers.

Subsequent to the nonmarine deposition, but also in the Late Cretaceous, the sea transgressed and resulted in deposition of the marine Point Loma and Cabrillo Formations (Kennedy and Moore, 1971) over conglomeratic Lusardi-Redonda rocks in the immediate San Diego area. The Point Loma Formation consists of sandstone and shale that was deposited on the outer continental shelf or slope as revealed by studies of benthonic Foraminifera (Kennedy and Moore, 1971). A
slight regression of the sea may have occurred before or during deposition of sandstone and conglomerate of the overlying Cabrillo Formation. Based on the presence of coarse-grained sandstone and conglomerate, Kennedy and Moore (1971) suggest that the Cabrillo Formation was laid down closer to the Cretaceous shoreline than the underlying Point Loma Formation. The Cabrillo Formation marks the uppermost Cretaceous beds found in the San Diego area. Rocks indicative of the Point Loma or Cabrillo Formations have not been reported in the Coronado Islands area, however, if the westward dip of unit n-1 of North Island continues to the edge of the Coronado Escarpment, one may expect to find Upper Cretaceous marine rocks on the sea floor west of North Island.

Regional Paleogene History

Except for the Eocene, Early Tertiary history of coastal southern California and Baja California is not well known due to gaps in the rock record. Paleocene rocks are absent except in Orange and Los Angeles Counties. Evidently, broad uplift resulting in subaerial erosion characterized the coastal region, at least during Late Paleocene time.

During the Eocene, fans of nonmarine and marine
sediment built up along the coast in the San Diego and Los Angeles areas. In the San Diego-Tijuana area this sediment from the east was deposited unconformably upon an erosion surface underlain by Cretaceous sedimentary rocks and the crystalline basement complex. Both areas received a large amount of material by subaerial transport across the northern Peninsular Ranges. Some debris was eroded from the local basement complexes, but a large volume was derived from sources east of the batholith (Delisle and others, 1965; Merriam, 1968; Woodford and others, 1968; Minch, 1972). The Eocene rocks along the present coast are nonmarine to shallow marine. An offshore, deep water facies of coastal Eocene rocks crops out on San Nicolas Island 150km west of Los Angeles (Cole, 1970). In the Eocene the San Nicolas Block may have been situated either adjacent to the Los Angeles Eocene fan (Yeats, 1973; Yeats and others, 1974) or off the San Diego area (Howell and others, 1974).

Oligocene rocks are not exposed along the coast except in the Los Angeles area and in the Transverse Ranges where the continental Sespe Formation underlies transgressive rocks of Miocene age. Much of the coastal region from Los Angeles to Northwestern Baja California was subjected to subaerial erosion between Upper Eocene
and middle Miocene time.

Local Paleogene History

In the greater San Diego-Tijuana area a gap exists in the rock record between the Late Cretaceous and early to possibly middle Eocene time. Eocene rocks of the La Jolla and Poway Groups (Kennedy and Moore, 1971) in the San Diego area, and the Delicias and Buenos Aires Formations east of Tijuana (Flynn, 1970), directly overlie Rosario Group rocks and the plutonic-metamorphic basement rocks of the region. Prior to Eocene deposition a deeply weathered erosional surface developed on the Cretaceous and older rocks (Gastil, 1961; Minch, 1970; Peterson and Nordstrom, 1970; Peterson and Abbott, 1973). By middle Eocene time a relatively narrow shelf existed in the San Diego area and several transgression-regression cycles resulted in an interfingering of marine and nonmarine rocks (Kennedy and Moore, 1971; Kennedy, 1973). At this time the exotic Poway Suite of clasts, derived from a source east of the batholith, were transported across the batholith to the San Diego area by several river channels (Minch, 1972). Sediment deposition was extensive during the Eocene and undoubtedly extended to points west of the Coronado Islands. Although in situ
Eocene rocks have not been reported on the immediate Borderland, reworked Poway Suite clasts, derived from the west, are numerous as reworked clasts on Middle and South Coronado Islands.

Regional Neogene History

During the Miocene and Pliocene Epochs intense tectonic activity replaced the stable continental shelf conditions that characterized the Continental Borderland in the Early Tertiary. The most notable results of this tectonism were (1) widespread rifting of the Borderland, (2) the uplift and exposure of once-subducted Catalina Schist rocks, (3) the subsequent erosion and deposition of Catalina Schist and other pre-Middle Tertiary rocks into structurally controlled troughs and basins, and (4) the advent of extensive basaltic and andesitic volcanism.

Miocene rocks crop out along the present coastline in the Rosarito Beach area south of the International Border (Minch, 1967), from Oceanside into southern Orange County (Woodford, 1925), and in the Los Angeles and Ventura Basins (Yerkes and others, 1965; Vedder and others, 1969 respectively). Especially thick sections of Miocene sediments accumulated in the Los Angeles basin (Yerkes and others, 1965). Miocene
Sedimentary and volcanic rocks are found on most of the islands off southern California, including Santa Rosa, Santa Cruz, Anacapa, Santa Catalina, and San Clemente islands (Emery, 1960), and off Baja California on the Coronado Islands (this report). Submerged portions of the Borderland contain Miocene rocks on nearly all of the topographic highs (Emery, 1960). Sedimentary rocks include shale, limestone, chert, sandstone, and conglomerate of early to late Miocene age, whereas, the volcanic rocks are mostly of middle Miocene age (Emery, 1954, 1960).

Along the coast, volcanic rocks crop out in the Rosarito Beach area (Minch, 1967; Minch and others, 1970), in Orange County (Schoellhammer and others, 1954; Yerkes, 1957), and in the Los Angeles-Ventura area (Shelton, 1954, 1955; Eaton, 1958). In the Borderland province volcanism was widespread and appears to have been concentrated near zones of major faulting. The Borderland from the Channel Islands southward to the Santo Tomas Fault off Baja California (Fig. 48) contains three northwest-trending structural zones (Moore, 1969). Moore describes these areas as (1) an outer faulted zone including the Patton Escarpment as its major feature, (2) a central zone delineated by faults south of San Nicolas Island and west of San
Figure 46. Structure of the Southern California Continental Borderland (Moore, 1969).
Clemente Island where folding rather than faulting is predominant, and (3) an inner faulted zone extending to the Mainland from the fault west of San Clemente Island (Fig. 48). The central folded zone appears to have a paucity of volcanic rock masses compared to the faulted zones on either side (Moore, 1969). Similarly, Krause (1965) reported concentrations of volcanic rocks near major fault zones in the area of the Santo Tomas Fault in the southern Borderland region, and Shelton (1954) described volcanism in the Transverse Ranges as having a close proximity to major zones of deformation.

Miocene sedimentary rocks of the Mainland and Borderland areas represent a wide variety of depositional conditions from quiet water chert and limestone deposition to turbidite and mudflows, but the rock group most indicative of Miocene tectonism is the San Onofre Breccia and its lateral equivalents. These rocks, noted for their coarse texture and abundance of Catalina Schist clasts, crop out at widely scattered localities from the Channel Islands, southward along the coast to the Coronado Islands (Fig. 49). At its type locality near San Onofre Mountain north of Oceanside, the San Onofre Breccia is in part nonmarine and interbedded with marine Miocene rocks (Woodford, 1925). San Onofre-type breccias are also located on
Figure 49. Distribution of San Onofre Breccia Outcrops in Southern California and Northwestern Baja California.
Point Dume southeast of Ventura (Woodford and Bailey, 1928), on Anacapa Island (School, 1959), on Santa Cruz Island (Rand, 1931; Bremner, 1931), and on Santa Rosa Island (Avila, 1968; Weaver, 1969; Yeats, 1970). The conglomerate beds of South Coronado Island were noted by Woodford (1925) as a possible southern continuation of the San Onofre Breccia. Also, Minch (1967) reported Catalina Schist debris in sandy middle Miocene rocks west of Rosarito Beach in Baja California. Although the San Onofre Breccia at the type locality is apparently lower Miocene (Woodford, 1925), the other outcrops outlined above are middle Miocene in age. Woodford proposed a western source area for the type locality, since no source area for Catalina Schist exists to the east. Portions of the San Onofre at the type locality have a red earthy matrix and Catalina Schist clasts up to 3m diameter, hence, Woodford concluded that the breccia debris was transported to the site of deposition by streams, slumping, and mudflows. Woodford also assumed the source area for these rocks to be an upland of high relief underlain by Catalina Schist bedrock that was not more than a few kilometers west of the present coastline. Similar upland areas supplied debris to the San Onofre deposits 150km to the west at Point Dume (Woodford and Bailey, 1928) and the Channel
Islands (Rand, 1931). Woodford and Bailey (1928) postulated the unlikeliness of Catalina Schist basement being present any further north than a line marked by the southern edge of the Santa Monica Mountains. This northern regional limit of Catalina Schist basement has been challenged, however, by Yeats (1970) who stated, on the basis of paleocurrent and lithologic data, that San Onofre Breccia on Santa Cruz Island was derived from the north in the area of the Santa Barbara Channel. Howell and others (1974) proposed that this part of Santa Cruz Island may have been moved northwest by strike slip faulting relative to a Catalina Schist source area west of Los Angeles. In fact there may have been several highlands that shed Catalina Schist debris in different directions.

Catalina Schist was first deposited as clasts in early Miocene time (Woodford, 1925; Yeats, 1968a, 1973). Uplift of the Catalina Schist basement must have commenced (at least locally) toward the end of the Oligocene, and continued through middle Miocene time when the bulk of San Onofre-type debris was deposited. The only regional subaerial remnants of this uplifted schist basement crop out on the Palos Verdes Peninsula and on Santa Catalina Island (Woodford, 1924)(Fig. 47, p. 158). Dredge hauls from suspected Catalina Schist
basement terrains have yielded characteristic blueschist and greenschist rocks from the Santa Catalina Island area, from thirty mile and forty mile banks west of the San Diego Trough, and from sixty mile bank west of San Clemente Basin (Emery and Shepard, 1945)(Fig. 50). Winterer and others (1969) dredged the outer Continental Borderland and Patton Escarpment and recovered altered graywacke, chert and diabase of probable Franciscan/Catalina Schist origin. Catalina Schist is also believed to underlie the Los Angeles Basin (Yeats, 1973; Yeats and others, 1974), and possibly the Santa Barbara Channel (Yeats, 1970).

Hill (1971) deduced from the occurrence of Franciscan/Catalina Schist in southern California and on the San Benito Islands 1000km to the south, that these basement rocks may be present offshore along most of the length of Baja California. Hill's proposed contact between Franciscan/Catalina Schist and Peninsular Ranges basement lies offshore from Laguna Beach southward along the Baja California coast (Fig. 47, p. 158). Aside from being presently covered by the sea, the area of contact has been subjected to Late Cenozoic erosion, subsidence, faulting, folding, and thick sedimentary and volcanic accumulations. However, the San Onofre facies along the coast from Rosarito
Figure 50. Bedrock Geology of the Southern California Continental Borderland (Emery, 1960).
Beach to Laguna Beach north of San Juan Capistrano delimits a relatively narrow zone of deposition between the Peninsular Ranges and the proposed Miocene highland(s) to the west. At all localities along the coast the San Onofre overlies Cretaceous to middle Miocene rocks which in turn overlie the Peninsular Range basement (Yeats, 1973), yet the large size of some Catalina Schist clasts indicates a close proximity to the upland on the west. Based on this textural and spatial data of the San Onofre Breccia, Yeats (1973) stated that the Peninsular Ranges-Catalina Schist basement boundary approximately coincides with the southeastward extension of the Newport-Inglewood deformation zone. The original juxtaposition of these genetically different rocks is best explained by underthrusting of Franciscan/Catalina Schist rocks beneath the continent in Mesozoic time along the proposed southern California subduction zone of Hill (1970). Thrusting along this zone ceased by late Cretaceous time, since Upper Cretaceous deposits are inferred to overlie the contact southeast of Newport Beach (Hill, 1970). Subsequent to subduction, such a fault zone would conceivably remain weak and be subject to strain from later tectonic forces of different stress fields. In Recent times right lateral slip has
occurred along the Newport-Inglewood deformation zone (Hill, 1970; Yeats, 1973). Similarly, uplift of the Catalina Schist basement in the Miocene could have taken place along the northern parts of the southern California subduction zone. This model is consistent with observed lithology, texture and limited areal extent of the San Onofre Breccia.

Uplift on the Continental Borderland was probably caused by a combination of isostatic rebound of the once subducted Catalina Schist during late Oligocene to early Miocene time, together with extensive crustal dilation of the area in the early through middle Miocene. Subduction along the continental margin must have waned by Miocene time to allow such an uplift. The termination of underthrusting along the west coast is generally associated with the encounter of the North American Plate with the active spreading center (East Pacific Rise) separating the Farallon and Pacific plates (McKenzie and Morgan, 1969; Atwater, 1970). Atwater (1970) presented two models for Cenozoic crustal interaction along western North America. One theory assumes a somewhat constant relative motion (right lateral strike slip) between the Pacific and North American plates at least as far back as the Middle Cenozoic. As the Pacific and North
America plates came together this relative motion resulted in strike slip faulting between two diverging ridge-trench-transform triple junctions, one of which migrated south, the other north. The other model proposes that the Pacific and North American plates, though abutted, remained stable relative to one another until 5 m.y. ago when strike slip motion was initiated along the San Andreas system. Lipman and others (1970) reported a general waning of calc-alkalic intermediate composition volcanism (assumed to be associated with subduction) in the west and southwestern United States by the end of the Oligocene. Lipman and others also noted an absence of andesitic volcanism through Pleistocene time along an ever-widening gap in the western United States. This is consistent with Atwater's proposed lengthening contact of the North American and Pacific plates south of the Mendocino Fracture Zone. Employing either of Atwater's models, subduction of the Farallon Plate was complete in the southern California area by about 27 m.y. ago or toward the end of the Oligocene.

The Continental Borderland area was not appreciably disrupted immediately after subduction ceased. The lower Miocene rock record in the Los Angeles area indicates shelf depositional conditions
similar to those of the Paleogene (Yeats, 1968a, 1968b, 1973), however, initial deposition of San Onofre Breccia-type debris in Saucesian time (Yeats, 1973) indicates a beginning of uplift and rifting in the Borderland. By middle Miocene time rifting and uplift resulted in widespread volcanism and coarse clastic sedimentation in lowlying areas.

The middle Miocene diastrophism of the Continental Borderland has been attributed to the East Pacific Rise, that presumably maintained active crustal upwelling, spreading, and volcanism as it was overridden by the North American Continent (Yeats, 1968a, 1968b). In this model continental crust would be rifted by deep-rooted spreading forces in the mantle, resulting in the characteristic block faulting of the Continental Borderland and Basin and Range provinces. In recent years it has been hypothesized and generally accepted that the oceanic spreading centers may, in fact, play a more passive role in the plate tectonics scheme, in that the lithosphere at spreading areas may be subject to tensional stress rather than convective upwelling. Regarding western North America, Atwater (1970, p. 3526) states,

In plate models, a spreading ridge is considered to be just the weakest place between 2 diverging plates; it is not especially
related to a convective up-welling zone in the mantle. Thus, when the Farallon plate ceases to exist, the ridge also ceases. This idea is incompatible with hypotheses which relate continued activity of the overrun East Pacific Rise to rifting in the Gulf of California and the Basin and Range province. (p. 3526)

Atwater suggested that most Pacific-North American interaction in the southern California area took place offshore where the two plates remained thin and warm until 5 m.y. ago when major movement was taken up by the San Andreas-Gulf of California system. Atwater also interpreted Miocene rifting in the Borderland to be a result of oblique spreading of crustal plates caused by nonalignment of the plate juncture relative to the mainly right lateral motion between the North American and Pacific plates. This proposal is strengthened by Howell and others (1974) who concluded that San Onofre Breccia of Santa Cruz Island and Eocene beds of San Nicolas Island can be linked to prospective source area north of Santa Catalina Island and near San Diego respectively by employing a model of largely right lateral strike slip. On the other hand, Yeats and others (1974) claimed that a palinspastic reconstruction of the Borderland, so as to realign pre-middle Miocene sedimentary facies of the northern Peninsular Ranges, Santa Monica, and Channel Islands blocks, requires largely east-west crustal movement.
Yeats (1968a) cited as evidence of east-west extension and rifting, the left lateral offset of 80km or more between lower Miocene facies of the Peninsular Ranges Block and the Santa Monica Block, and the apparent lack of marine facies to the west for Paleogene rocks of western Orange and Los Angeles counties. By schematically moving the Santa Monica Block eastward 80km and by tucking the Channel Islands Block against the Anaheim Nose, Yeats and others (1974) restored continuity of lower Miocene facies boundaries and provided for a nearby, deep water equivalent (Eocene deposits of San Nicolas Island) of the continental delta deposits of the Northern Peninsular Range Block. The east-west-trending Santa Rosa Island-Malibu Coast and related fault zones may be an intracontinental transform structure (Davis and Burchfiel, 1973) separating a zone of lateral extension (the Continental Borderland) from the Transverse Ranges which experienced negligible crustal dilation. Since the Channel Islands Block was part of the North American Plate prior to rifting, Yeats and others (1974) deduced that rifting of the Borderland took place independently within the North American plate. This does not rule out, however, the possibility of strike slip between the Pacific and North American plates occurring offshore, perhaps near
the present continental rise.

As noted by Scholz and others (1971), two situations in present plate tectonics models result in diametrically opposed separation of crustal blocks. One is the familiar ridge or rise spreading, the other is crustal dilation in certain interarc basins as described by Karig (1970, 1971a, 1971b). In the western Pacific Karig observed high heat flow and apparently young basaltic crust behind several active island arcs. The mechanism that creates spreading in interarc basins is hypothesized by Karig as a subduction-related diapir of hot material that migrates upward from the subduction zone at depth and spreads laterally as it encounters the brittle crust. If regional compression caused by plate convergence has ceased, or if such compression can be relieved landward of the arc, then crustal dilation of the interarc basin will result. Scholz and others (1971) suggested such an interarc spreading model (of an ensialic nature) to explain the block-faulting of the Great Basin province of the western United States. Evidence presented by Scholz and others to support this model includes (1) the initiation of crustal spreading in the Great Basin coincides with the termination of subduction along the west coast using the models of McKenzie and Morgan.
(1969) and Atwater (1970); (2) a regional changeover from predominant calc-alkaline volcanism to basaltic extrusion in the region beginning in late Oligocene (Christiansen and Lipman, 1972); (3) the presence of a low velocity layer in the upper mantle of the province; and (4) the anomalously thin crust (30km as opposed to 40km in surrounding provinces) in the Great Basin area. This theory of a laterally spreading diapir is further substantiated by the paucity of Recent faulting and volcanism in the central Great Basin and an abundance of such activity in Recent and Quaternary time in the eastern and especially the western margins of the province (Scholz and others, 1971). McKee (1974) placed the beginning of major basaltic volcanism and related crustal extension for the central and southern Great Basin at no earlier than 21 m.y. ago. According to McKee, most movement on the Basin and Range faults, particularly those near the outer edges of the province, has occurred since 7 m.y.b.p. In summary, Scholz and others (1971) suggested that the subduction-initiated diapir of hot mantle and crustal material welled upward by the Paleogene and spread laterally beneath the crust, but could not disrupt the crust (except for some minor faulting and forceable calc-alkaline volcanism) since compressional forces prevailed in the region. As
subduction ceased along an ever-widening zone along the west coast, compressive stress was relieved and the extensional stress field of the interarc diapir was able to disrupt the continental crust.

The ensialic interarc basin spreading model has been proposed by Yeats and others (1974) as a possible mechanism for development of the California Continental Borderland. Yeats and others envision intracontinental spreading in the middle Miocene that caused the continental crust of the Borderland to separate into blocks, whereas, the underlying Catalina Schist (presumably in fault contact with the continental crust) was thinned with a minimum of rifting due to a relatively high ductility. Both the Continental Borderland and the Great Basin have undergone extensional block faulting and basaltic volcanism that commenced in late Oligocene to early Miocene time. The portion to the southern end of the Great Basin delineated by the Garlock Fault and the band of east-west oriented faults that separate the Transverse Ranges from the Continental Borderland have been presented as possible intracontinental transform features by Davis and Burchfiel (1973). These fault zones separate the relatively unriifted areas of the Mojave Block and the Transverse Ranges from the block faulted Great Basin and Continental
Borderland areas respectively. The Great Basin has undergone internal extension as has the Borderland (Yeats and others, 1974), therefore, lateral offsets should vary in magnitude at different points along those fault zones. Lateral displacements along the Garlock Fault are greatest at the west end of the fault and decrease to almost no displacement in the vicinity of Death Valley (Davis and Burchfiel, 1973). Similarly, the lack of appreciable offset of the continental rise (Patton Escarpment) west of the Channel Islands indicates to Davis and Burchfiel that rifting in the Borderland probably increased in magnitude from west to east. A left lateral offset of 80km has been documented along the Malibu Coast-Santa Monica fault system (Yeats, 1968a, 1968b, 1973; Yeats and others, 1974), but a right lateral displacement of 150km between the Channel Islands Block and the Santa Monica Mountains along westward extensions of this fault zone is necessary in the rifting hypothesis of Yeats and others (1974). It is evident that internal spreading of the Borderland, rather than lateral movement between the Transverse Ranges and the Borderland as a whole has been the primary tectonic process producing these laterally opposed displacements.

By removing the estimated 250km of right
lateral slip along the San Andreas and related fault systems, the Continental Borderland roughly lines up with a southward continuation of the Great Basin. It is necessary, though, to include the relatively unrifted Transverse Ranges and the Mojave Block between the Great Basin and the Borderland provinces in any palinspastic restoration. Employing the ensialic spreading model, it is possible that between the Santa Cruz Island-Malibu Coast-Santa Monica faults and the Garlock Fault, Middle to Late Tertiary subduction-related diapir(s) were not active, or perhaps these areas did not experience enough release from the compressive stress field to permit crustal dilation.

Even though rifting and volcanism in the Great Basin and Borderland provinces coincides with the termination of subduction along the west coast, the timing of major diastrophism of the two regions differs. The majority of crustal extension of the Borderland occurred in the time interval from 16 m.y. to 13 m.y. ago (Yeats and others, 1974), but the Great Basin has been more active in the last 7 m.y. than in early Neogene time (McKee, 1974). The ensialic interarc basin spreading model as applied to the Continental Borderland is speculative at this time, but deserves scrutiny as a working hypothesis.
The widespread volcanism and coarse sedimentation that occurred on the Continental Borderland in middle Miocene time had waned by the late Miocene time. The Catalina Schist-cored uplands of the Borderland, no longer shedding San Onofre-type debris, had most likely undergone a combination of tectonic foundering, active erosion, and masking by volcanic flows. According to Yeats (1968a, 1968b, 1970, 1973) the original Catalina Schist highs may have been ductile piercement ridges that welled up from below in the early stages of rifting, but subsequently subsided as rifting widened.

Shelf and basin deposition and some volcanism continued in the Continental Borderland into Pliocene time. By then the horst-graben topography was well developed, hence, most Pliocene to Recent sedimentation has been confined to nearshore shelves and embayments, and offshore troughs and basins. Little sedimentation has occurred since the Miocene on the ridge tops, as indicated by the presence of Miocene Foraminifera in phosphorite dredged from many topographic highs (Emery, 1960). During the Pliocene the Ventura Basin, Los Angeles Basin, and the San Diego Embayment were sites of particularly thick sedimentation. These nearshore areas exhibit some subaerial outcrops today, but thick
sections of Pliocene sediment undoubtedly lie beneath Pleistocene and Recent sediment in the offshore basins (Fig. 50, p. 175).

Volcanism in the Pliocene, though not nearly as widespread as in the middle Miocene, occurred near fault zones both on the mainland and to a greater extent on the Borderland. The Santa Rosa basalts near Murietta, California are in close proximity to the Elsinore Fault and were extruded 8.3 ± 0.5 m.y. ago (Hawkins, 1970b). Basaltic rocks dredged from Northeast Bank 200km west of San Diego on the outer Borderland were dated at 4.5 ± 0.5 m.y. (Hawkins and others, 1971).

With the advent of major spreading at the mouth of the Gulf of California about 5 m.y. ago (Case and others, 1970; Larson, 1970), right lateral shear became the dominant tectonic force applied to the Borderland. According to Atwater (1970) the youngest magnetic anomaly off the west coast of Baja is 11 m.y. old, hence, the spreading in the Gulf of California was preceded by 5 to 7 m.y. of deformation and cooling of the main Pacific-North American plate interface along the lower Baja coast and the Continental Borderland. When major right lateral motion was taken up east of Baja California, the Peninsular Ranges may not have moved as a unit away from the Gulf of California.
spreading centers (Garfunkel, 1973; Normark and Curray, 1968). Some of the right lateral stress is relieved along faults west of the main San Andreas zone such as the San Jacinto, Elsinore, Newport-Ingleswood, and San Clemente Island faults in the southern California area and the Agua Blanca and San Miguel faults in northwest Baja California. This strain diversity, occurring since the advent of major spreading in the Gulf of California into Recent times, may be caused by either a slow eastward migration of spreading centers and related northwest-southeast strike slip movement, by compression in the area of the Transverse Ranges (Garfunkel, 1973), or perhaps the Peninsular Ranges and Continental Borderland are, even at present, not ridgedly attached to the Pacific Plate. In any case, Gulf of California spreading in the Pliocene did not transfer all right lateral stress inland to the San Andreas zone. This resulted in structural modification of the Borderland area by right lateral strain.

**Local Neogene History**

The Miocene rock record is locally represented by the Rosarito Beach Formation in the La Mision-Rosarito Beach-Tijuana area (Minch, 1967; Minch and others, 1970), the Otay Formation (Artim and Pinckney,
1973) in the south San Diego-International Border area, and rocks of Middle and South Coronado Islands (Emery and others, 1952; this report). Oligocene rocks are absent in the region as a result of nondeposition or erosion prior to the middle Miocene. In the south San Diego-Tijuana-Rosarito Beach area middle Miocene deposits unconformably overlie Eocene and older rocks. Offshore, the middle Miocene rocks of the Coronado Islands and surrounding area were certainly deposited above Peninsular Ranges basement and Cretaceous sedimentary rocks and probably directly overlie Lower Tertiary deposits as well. Although direct observation of the relative stratigraphic position of the Rosarito Beach Formation and the Coronado Islands rocks is not possible, the author believes the Coronados section to be older than the Mainland rocks based on lithologic, paleogeographic and structural interpretations outlined below.

The generalized structure of the Coronado Islands and the nearby coastal area is that of west-tilted fault blocks separated by east-dipping faults that expose older rocks to the west. The uplifted southern half of South Island is an exception. The unit m-1 redbeds of the western margin of Middle Island, thus, are probably the stratigraphically lowest Miocene rocks
of the region. Eocene and earlier rocks of the Borderland were shed eastward from the uplifted highlands to the west. The highland source area was shedding a mixed suite of reworked Peninsular Ranges and Poway-type clasts and a small amount of Catalina greenschist and blueschist debris. As with all Miocene rocks of the Islands, these red beds contain a high percentage of volcanic rock fragments from nearby extrusive source areas. The sea transgressed over the Coronado Islands area as tectonic disruption of the Borderland continued and remained at least through deposition of unit s-6, the youngest Miocene unit of the islands. This invasion by the sea could have been of eustatic origin, but the immediate depositional trough or basin was in all probability a rift valley. Although no direct correlation is possible, rocks of Middle and South Island that bear a resemblance to one another are (1) sandstone and shale of units m-2 and s-1; (2) sandstone and conglomerate of units m-3 and s-3; (3) conglomerate and conglomeratic sandstone of units m-4 and s-4; and (4) the volcaniclastic breccia of units m-5 and s-5. Either parts of these units are correlateable or the depositional succession was repeated, once for the Middle Island, and again for units s-3 through s-5 of South Island. Assuming the succession was not repeated,
units m-2 and s-1 are probably the next highest stratigraphic units above the unit m-1 redbeds. Unit m-2 is predominantly medium-grained sandstone and unit s-1 is over 60% shale. Given the close proximity of unit m-2 to unit m-1, and the likelihood that sandstone-siltstone deposition would precede shale deposition in a transgressive marine environment, unit m-2 is probably older than unit s-2. Thus, the interval of time between deposition of conglomeratic rocks of units m-1 and s-2 was marked by quiet marine deposition (units m-2 and s-1). Conglomerate debris once carried to the area by streams was being dumped farther to the west near the shoreline of the western highland, and the Coronado Islands area was receiving only fine sediment. These quiet depositional conditions were only temporary, since the western highland continued to rise relative to the immediate depositional area, and a subsea fan was prograding eastward. This process is reflected in the sharp contact between the shale of unit s-1 and the coarse conglomeratic sandstone of unit s-2. High energy conditions then prevailed. Material from the west was deposited in the immediate structural trough. However, directly to the east on the Mainland the basal Mira Al Mar member of the middle Miocene Rosarito Beach Formation contains some Catalina Schist clasts, and
Figure 51. Middle Miocene Paleogeography of Coronado Islands and Surrounding Area.
overlying basalt of the same formation was derived from the west (Minch, 1967). This indicates, along with paleoslope and paleocurrent data from the Coronado Islands, that an east to northeast-dipping paleoslope prevailed in the region throughout middle Miocene time, thus precluding any appreciable sediment influx from the east.

Employing the prograding fan model, it is inherent that sediment of the Coronado Islands was laid down prior to deposition of the Rosarito Beach Formation. Indeed, markedly different lithologic properties of Catalina Schist debris and volcanic rock in the two areas suggests that deposition was not contemporaneous. Catalina Schist material in the basal member of the Rosarito Beach Formation includes a large percentage of blueschist clasts averaging 1 to 15cm diameter with some up to 40cm diameter (Minch, 1967). Minch (1967) reported the basal sandstone beds locally contain up to 20% heavy minerals, half of which are glaucophane grains. Conversely, greenschist is the dominant Catalina Schist rock type on the Coronado Islands. Blueschist clasts are rare in conglomerate beds, and no glaucophane grains were found in sandstones of the islands. Since both localities received debris from the west, a proportionately greater area of blueschist
(relative to greenschist) bedrock must have been exposed in the western uplands during deposition of the Rosarito Beach Formation. Volcanic rocks of the Coronados and the Mainland differ in composition. Most clasts of volcaniclastic breccias of the Islands are andesitic basalts that contain a low percentage of ferromagnesian minerals. Volcanic rocks of the Rosarito Beach Formation are basalt flows with average ferromagnesian mineral percentages of; augite 20 to 25%, magnetite 4 to 9%, and olivene 4 to 9% (Minch, 1967). When the Rosarito Beach basalts were extruded, rifting of the Borderland had probably reached a more advanced stage than was present during deposition of the Coronado Islands rocks. Minch and others (1970) reported a radiometric age of $14.3 \pm 2.6$ m.y.b.p. for the lower part of the Costa Azul Member of the Rosarito Beach Formation. This age date coincides with the time of major rifting in the northern Borderland, reported by Yeats and others (1974) as taking place 13 to 16 m.y. ago. A comparison of this age against a fossil-based Saucesian to lower Mohnian age determination of South Island rocks is complementary, but does not in itself strongly substantiate a younger age for the Rosarito Beach Formation. This is due to uncertainties in correlating faunal time zones and millions of years.
Minch (1967) proposed a westward source area for the basalt of the Rosarito Beach Formation based on inclined vesicles in some flows. These rocks are tilted only slightly to the west, are quite resistant to weathering and form plateaus in the Tijuana-Rosarito Beach area. Tilting and faulting in the Coronado Islands area has been more severe than along the coast. Had basalt similar to the Rosarito Beach deposits been extruded in the Coronados area, one would expect these rocks to be present as islands today. The existence of the Coronados is entirely based on the erosion resistance of units n-1, m-1, and s-2. In this light, the author believes that a source for the Rosarito Beach volcanics may have been situated between the present coastline and the Coronado Islands. Another possibility is that strike slip faulting occurred between the Islands and the mainland, thus moving the basaltic source area northward relative to the Mainland. These ideas are speculative but can be tested by more detailed study of the offshore area.

Miocene rocks in southwestern San Diego County have been recognized only recently. The Otay Formation, described by Artim and Pinckney (1973), is a 30 to 50 m thick deposit of volcaniclastic sandstone and bentonite in the Otay Mesa area that overlies flat-laying Eocene
deposits. Foster (1974) has mapped the Otay in the San Ysidro area west of Otay Mesa. Both authors correlated the Otay with the Rosarito Beach Formation.

The Pliocene Epoch was a time of local shallow marine deposition, and structural deformation along the coast and local offshore area. Pliocene deposits, though not found in the immediate vicinity of the Coronado Islands, are present on Coronado Bank 15km north of the islands (Emery and others, 1952). In the San Diego area the Pliocene San Diego Formation unconformably overlies Miocene and older rocks (Hertlein and Grant, 1944). Southern equivalents of the San Diego Formation unconformably cap Miocene and older rocks in the areas of San Ysidro (Foster, 1974), Otay Mesa (Artim and Pinckney, 1973), and Tijuana-Rosarito Beach (Minch, 1967). The San Diego Formation is mostly fine- to medium-grained silty sandstone with some conglomerate and shale deposited in a shallow marine environment. Offshore, Emery and others (1952) recovered Pliocene fossils from in situ sedimentary rock of the Coronado Bank north of Coronado Canyon (Fig. 1, p. 2).

The Tijuana-Rosarito Beach area underwent faulting and tilting prior to deposition of the San Diego Formation (Minch, 1967). Faults also cut the
Pliocene rocks and to a lessor extent have displaced Pleistocene terrace deposits (Minch, 1967). Minch (1967) stated "... the main period of faulting is believed to be Middle and Upper Miocene, with at least some major movement in the Upper Pliocene-Pleistocene time. Post Pleistocene movement has been (of) a relatively small magnitude" (p. 1173).

The general structural pattern of the Coronado Islands is similar to the Mainland near Rosarito Beach. In both areas northwest and northeast-trending, east-dipping normal faults predominate, though faulting and tilting was more intense on the islands. Hence, it is probable that major deformation in the immediate Mainland and offshore areas was caused by the same tectonic forces in Late Miocene through Pliocene time. By the close of the Miocene major east-west extension of the Borderland had ceased, its block faulted structure was well developed, plus the period of massive volcanic outpourings and San Onofre-type deposition had passed. Therefore, faulting of local middle Miocene rocks was probably caused by a different stress field than existed earlier in the middle Miocene. An attempt to document the timing and magnitude of regional stress changes is beyond the scope of this paper, but if right lateral relative movement between
the North American and Pacific plates has been taking place since the Middle Cenozoic as postulated by Atwater (1970), then a relaxation of east-west extension forces would allow the strike slip tectonics in middle Miocene time. Atwater (1970) stated that the Pacific Plate remained hot and thin for some time after initial Juncture between the Pacific and North American plates, thus relative plate motion was taken up along this zone until cooling (hence strengthening) allowed strike slip faulting to be transferred inland. Atwater (1970) said,

Thus, a cooling time must be introduced between the time that the triple junction passes a given point and the time when deformation related to the new boundary regime might be expected to be felt within the continent. For much of southern Baja California, there appears to have been a cooling time of 5 to 7 m.y., since the last anomaly offshore is 11 m.y. old, while spreading began inside the mouth of the Gulf 6 to 4 m.y. ago (Chase and others, 1970; Larson, 1970). During the cooling time, all American Pacific motion was apparently taken up along the continental margin. (p. 3526)

This process may have been the mechanism for Late Miocene-Pliocene disruption of the Coronado Islands and immediate Mainland. The local increase in the number of faults and fault offset magnitude in a westerly direction may indicate the conjugate normal faults of the Coronado Islands are near a major strike
slip zone further offshore, perhaps in the San Diego Trough or the San Clemente basin area.

Regional Quaternary History

The regional Quaternary sedimentation record is primarily fluvial, near-shore terrace, and shallow offshore deposits preserved in patchy outcrops. Of course, the near-shore basins and troughs contain hundreds of meters of Pleistocene to Recent sediment. The southern California coastal area and nearly all offshore islands contain remnants of Pleistocene wave built and/or wave cut terraces, and flat-lying deposits are now found at various levels below sea level (Emery, 1960). Ice age-related eustatic changes are generally considered as the dominant cause of regional sea level fluctuations, however, the presence of wave cut terraces 250m above and as much as 500m below sea level (Emery, 1960) is evidence of major tectonic movement.

The Continental Borderland and adjacent Mainland areas are still not completely welded to the Pacific Plate as evidenced by regional right lateral slip faults. On the Mainland the San Jacinto, Elsinore, Newport Inglewood, Agua Blanca, and San Miguel fault zones have been active in Pleistocene to Recent time. In the Borderland region faulting and tectonism has been
active in the Quaternary (Emery, 1960). The San Clemente Island fault, in particular, has been the site of several historical strike slip displacements. In addition, faulting and folding of Pleistocene deposits is well documented in several areas of the Borderland and Mainland (Emery, 1960).

**Local Quaternary History**

Pleistocene to Recent geologic activity in the San Diego-Tijuana-Coronado Islands area has been marked by continued faulting, sea level fluctuations, erosion along the coast, and fluvial to shallow marine deposition. The most widespread Pleistocene deposits are of the Lindavista Formation (Hanna, 1926) that caps Pliocene and older rocks of the coastal plateaus from northern San Diego to the Rosarito Beach area. The Lindavista is in most places less than 15m thick and is composed of red sandstone and conglomerate laid down during a Pleistocene regression of the sea. In the Late Pleistocene, after a period of subaerial erosion, the sea again transgressed to a much more limited extent to cut the La Jolla terrace and cause deposition of lagoonal sediment of the Bay Point Formation (Valentine, 1959) in low lying areas (Peterson, 1970). The Bay Point Formation crops out at its type locality
near Mission Bay (Valentine, 1959) and near the south end of San Diego Bay (Foster, 1974). Another regression of the sea left reddish brown terrace deposits along the La Jolla terrace and over the type locality of the Bay Point Formation (Peterson, 1970), and over the Nestor terrace in the San Ysidro and Tijuana areas (Foster, 1974; Minch, 1967). The red terrace deposits of South Coronado Island (unit st-2) are of comparable elevation and are composed of material similar to the Nestor and La Jolla terraces, but until more is known of the fossils of unit st-2 the correlation must remain tentative.

In the offshore area there has been continued sediment influx into the San Diego Trough and San Clemente Basins during Quaternary Epoch (Shepard and Einsole, 1962) as well as some near shore shelf deposition, especially on Coronado Bank (Emergy and others, 1952). The shelf surrounding the Coronado Islands is topographically higher than the Coronado Bank and was probably subject to more erosion. The Coronado and La Jolla canyons were also undergoing erosion during the Pleistocene Epoch (Emery and others, 1952).

The San Diego-Tijuana-Rosarito Beach and offshore areas have been tectonically active during the
Quaternary Epoch, though seismic activity in historic times has been minimal. Displacement and/or tectonic warping of Pleistocene deposits has been documented along the Rose Canyon Fault on the northeast side of Mount Soledad (Peterson, 1970), on the east side of the Point Loma Peninsula (Kern, 1973), along the La Nacion fault system in the Chula Vista-San Ysidro area (Artim and Pinckney, 1973; Foster, 1973), and in the Rosarito Beach-Tijuana area (Minch, 1967; Flynn, 1970). A case for present seismic activity along a proposed San Diego Bay-Tijuana Fault has been presented by Wiegand (1970) employing warm well water and microseismic data.

Faulting in the offshore region is not well documented, however, one would expect that appreciable Quaternary deformation has taken place between the Rose Canyon-San Diego Bay-Tijuana fault system and the San Clemente fault zone to the west. Coronado Bank has undergone deformation subsequent to being beveled by wave action in the Pleistocene, and the adjacent Loma Sea Valley may be of structural origin (Emergy and others, 1952). The timing of latest faulting of the Coronado Islands is not well defined. Only the fault along the west side of the down-dropped block of South Island is in immediate contact with Pleistocene
deposits (Plate III). Even at this locality it is not clear whether unit st-2 has been faulted. The answer may be found if a trenching operation were undertaken, however, the author was reluctant to scar the landscape with such a project. In any case, most movement on the fault occurred before unit st-2 was deposited. In the Pleistocene it was essential that the beds of unit s-3 and s-2 be present in their present position in order to shelter the Puerto Cueva Cove area and allow deposition on the terrace and to protect the central fault block from wave erosion.
REFERENCES CITED
REFERENCES CITED


Anonymous, 1924, Informe sobre la exploracion geologica de la Baja California, por la Mariand Oil Company de Mexico: Bol-Petrol, v. 17, no. 6, p. 417-453, b. 18, no. 1, p. 14-53.


Bellemin, G. J., and Merriam, R. H., 1958, Petrology and origin of the Poway Conglomerate, San Diego
County, California: Geol. Soc. America Bull., v. 69, p. 199-220.

Bremner, 1931, Geology of Santa Cruz Island, Santa Barbara County, California: Santa Barbara Museum of Natural History Occasional Papers, no. 1, 33p.


______, 1970b, Petrology and possible tectonic significance of Late Cenozoic volcanic rocks, southern California and Baja California: Geol. Soc. America Bull., v. 81, p. 3323-3338.


Minch, J. A., 1967, Stratigraphy and structure of the Tijuana-Rosarito Beach area, northwestern Baja


The Coronado Islands are four tilted fault blocks located on a shallow submarine shelf 25km southwest of San Diego, California. The islands lie en echelon to one another along a north-northwest trend.

North Island lies 7km northwest of South Island and is the westernmost island of the group. North Island is 1.5km long and is composed of 200+m of red sandstone and shale that dips west 20 to 30°. Since clasts of the Eocene Poway Suite (found as reworked clasts in all post-Eocene rocks of the region) were not located on North Island, a pre-Eocene age is likely. North Island rocks are a probable westward equivalent of the Upper Cretaceous nonmarine Lusardi Formation redbeds of the nearby Mainland.

Middle Island and Middle Rock, located 1km west of South Island, are the smallest, yet most structurally complex of the Coronados. Twelve tilted fault blocks of varying attitudes dominate the structure of the island. The whole of Middle Rock and the western margin of Middle Island are composed of nonmarine red sandstone and conglomerate. Unlike the North Island rocks, these beds contain reworked Poway Suite cobbles
and Catalina Schist debris. The remainder of Middle Island contains beds of marine sandstone, shale, and conglomerate. An islet east of Middle Island is composed entirely of volcaniclastic breccia. A probable Miocene age is assigned the strata of Middle Island and Middle Rock on the basis of (1) the presence of Catalina Schist clasts, and (2) the lithologic similarity of some beds to known middle Miocene rocks of South Island.

South Island, the largest of the Coronados, is 3.5km long. Three main structural blocks of west-dipping strata comprise the island. The north and south blocks together contain over 250m of conglomerate and sandstone of the San Onofre Breccia facies. These beds contain various clasts of Catalina Schist and yield Foraminifera of middle Miocene age. The middle downdropped block is made up of conglomeratic sandstone, volcaniclastic breccia, siltstone, and sandstone of middle Miocene age. Sedimentary structures in San Onofre-type rocks of the island indicate north-northeast current-slope directions at the time of deposition.

Miocene rocks of Middle Rock, Middle Island, and South Island were derived from the west. In middle Miocene time uplift west of the Coronados exposed Cretaceous and Early Tertiary sediments as well as the
Catalina Schist complex. The rocks of these southern three islands were laid down as part of a sedimentary fan that prograded eastward in a subaerial, then submarine environment.
GEOLOGIC MAP and STRUCTURE SECTION of NORTH CORONADO ISLAND
NORTHWESTERN BAJA CALIFORNIA, MEXICO
SCALE 1:7000

FORMLINE TOPOGRAPHY FROM AIR PHOTOS
GEOLOGY BY TOM LAMB, 1974
PLATE 1
TOM LAMB
GEOLOGY OF CORONADO ISLANDS
GEOLOGIC MAP and STRUCTURE SECTION of MIDDLE CORONADO ISLAND, NORTHWESTERN BAJA CALIFORNIA, MEXICO

SCALE 1:5070

FORMLINE TOPOGRAPHY FROM AIR PHOTOS

GEOLOGY BY TOM LAMB, 1974

PLATE II

EXPLANATION

ROCK UNITS

M-5
VOLCANICLASTIC BRECCIA

M-4
SANDSTONE, SILTSTONE, SHALE, AND CONGLOMERATE

M-3
SANDSTONE, SILTSTONE, AND CONGLOMERATE

M-2
SANDSTONE, SILTSTONE, AND SHALE

M-1
SANDSTONE AND CONGLOMERATE

GEOLOGIC SYMBOLS

FAULT, DASHED WHERE INFERRED

STRIKE AND DIP OF STRATA

COLUMNAR SECTION TRAVERSE

PLATE II

TOM LAMB
GEOLOGY OF CORONADO ISLANDS