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Geology Of The Eastern Part Of The Regina Quadrangle, Sandoval And Rio Arriba Counties, New Mexico

Margaret Anne Merrick

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GEOLOGY OF THE EASTERN PART OF THE REGINA QUADRANGLE,
SANDOVAL AND RIO ARRIBA COUNTIES, NEW MEXICO

by

Margaret Anne Merrick

B.S., Colorado State University, 1976

THESIS

Submitted in Partial Fulfillment of the
Requirements for the Degree of

Master of Science in Geology

The University of New Mexico
Albuquerque, New Mexico

December, 1980
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ABSTRACT OF THESIS

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ABSTRACT

The Regina quadrangle is located in Sandoval and Rio Arriba Counties, New Mexico, along the boundary between the northwestern margin of the Nacimiento uplift and the east-central San Juan Basin. The uplift is composed of a core of Precambrian rocks overlain by a veneer of Mississippian through Triassic sedimentary rocks. Sedimentary rocks ranging in age from Jurassic to Tertiary are upturned along the margin of the San Juan Basin.

The Precambrian rocks in the area are primarily granite to granodiorite gneiss with xenoliths of mafic and felsic metavolcanic rocks and metasedimentary rocks. These rocks have undergone greenschist facies metamorphism. Late stage aplite dikes, mafic dikes, pegmatites and quartz veins are also present.

There are between 3,300-3,400 m (10,700 and 11,100 ft) of sedimentary rocks exposed in the eastern part of the Regina quadrangle. The Mississippian and Pennsylvanian rocks are shallow water marine limestone, sandstone and shale. The Permian, Triassic and Jurassic rocks include sandstone, shale, gypsum and minor limestone that were deposited in continental environments, and the Cretaceous rocks are shallow water marine and coastal swamp and lagoon deposits. The Tertiary rocks are mainly sandstone and shale that are the result of deposition in continental flood plains and alluvial fans. Late Tertiary and Quaternary sediments include alluvium, landslide, terrace and pediment deposits.
The Nacimiento uplift and the San Juan Basin are the two main tectonic features in the Regina quadrangle and the boundary between them is the synclinal bend of the San Juan Basin which has been cut by the Nacimiento fault. The Nacimiento fault is a north- to northeast-trending, high-angle reverse fault that has associated antithetic and synthetic faults as well as southwest- to northwest-trending faults that offset it.

These two tectonic features began development during Late Cretaceous time during the Laramide orogeny, when a monocline was formed between the uplift and the basin, probably as the result of shear folding over close-spaced vertical fractures in the basement rocks. Later uplift, in association with Rio Grande rifting, enhanced the structural relief between the basin and uplift, and resulted in the present configuration of the Nacimiento fault. There is a maximum of 900 m (3,000 ft) of stratigraphic separation along the Nacimiento fault, and a maximum of 3,350 m (11,000 ft) of structural relief between the basin and the uplift in the eastern Regina quadrangle.

Although there are no reports of economic mineral deposits in the eastern part of the Regina quadrangle, there is evidence of prospecting in the area. Minor copper and uranium are found in sandstones of the Madera and Abo Formations and thin beds of coal are present in the Menefee Formation of the Mesaverde Group.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>iv</td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td>vi</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>ix</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>Location and accessibility</td>
<td>1</td>
</tr>
<tr>
<td>Physiography</td>
<td>2</td>
</tr>
<tr>
<td>Methods</td>
<td>5</td>
</tr>
<tr>
<td>Previous work</td>
<td>5</td>
</tr>
<tr>
<td>Acknowledgments</td>
<td>6</td>
</tr>
<tr>
<td>ROCK UNITS</td>
<td>7</td>
</tr>
<tr>
<td>Precambrian rocks</td>
<td>7</td>
</tr>
<tr>
<td>Felsic metavolcanics</td>
<td>9</td>
</tr>
<tr>
<td>Mafic metavolcanics</td>
<td>14</td>
</tr>
<tr>
<td>Metasedimentary rocks</td>
<td>16</td>
</tr>
<tr>
<td>Gneiss</td>
<td>18</td>
</tr>
<tr>
<td>Dikes and veins</td>
<td>21</td>
</tr>
<tr>
<td>Aplitic dikes</td>
<td>21</td>
</tr>
<tr>
<td>Mafic dikes</td>
<td>23</td>
</tr>
<tr>
<td>Age</td>
<td>23</td>
</tr>
<tr>
<td>Metamorphism</td>
<td>25</td>
</tr>
<tr>
<td>Structure and mechanisms of emplacement</td>
<td>26</td>
</tr>
<tr>
<td>Mississippian System</td>
<td>28</td>
</tr>
<tr>
<td>Arroyo Peñasco Group</td>
<td>28</td>
</tr>
</tbody>
</table>

vi
Pennsylvania System ........................................ 31
Madera Formation .......................................... 31
Permian System ............................................ 33
Abo Formation ............................................. 33
Yeso Formation ............................................ 34
Triassic System ........................................... 36
Chinle Formation ........................................... 36
Jurassic System ............................................ 38
Entrada Sandstone ......................................... 38
Todilto Formation .......................................... 39
Morrison Formation ........................................ 40
Cretaceous System .......................................... 45
Dakota Formation ........................................... 45
Mancos Shale ................................................ 48
Mesaverde Group ........................................... 49
Lewis Shale .................................................. 52
Kirtland Formation and Fruitland Shale undivided .... 53
Tertiary System ............................................. 54
Ojo Alamo Formation ....................................... 54
Nacimiento Formation ....................................... 54
San Jose Formation ......................................... 55
Tertiary-Quaternary Deposits ............................. 56
Older alluvium ............................................. 56
Pediment deposits ........................................ 56
Quaternary Deposits ...................................... 59
Landslide deposits ........................................ 59
Alluvium ..................................................... 59
REGIONAL TECTONIC SETTING .......................... 60
STRUCTURES IN THE REGINA QUADRANGLE ............ 63
Nacimiento Uplift ......................................... 63
San Juan Basin ............................................. 69
STRUCTURAL ANALYSIS .................................. 71
Paleozoic Events ......................................... 71
Late Cretaceous and Tertiary Events ..................... 71
ECONOMIC GEOLOGY ...................................... 79
Copper ...................................................... 79
Uranium .................................................... 80
Coal ........................................................ 81
Gypsum ..................................................... 81
REFERENCES ............................................... 82
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Geology of the eastern part of the Regina quadrangle, Rio Arriba and Sandoval Counties, New Mexico</td>
<td>in pocket</td>
</tr>
<tr>
<td>2.</td>
<td>Geologic cross-sections of the eastern part of the Regina quadrangle</td>
<td>in pocket</td>
</tr>
<tr>
<td>3.</td>
<td>Surface and subsurface tectonic map of the northwest Nacimiento uplift, east-central San Juan Basin, southwest Gallina-Archuleta Arch, New Mexico</td>
<td>in pocket</td>
</tr>
<tr>
<td>4.</td>
<td>Location of the eastern part of the Regina quadrangle</td>
<td>3</td>
</tr>
<tr>
<td>5.</td>
<td>Detailed location map of the eastern part of the Regina quadrangle</td>
<td>4</td>
</tr>
<tr>
<td>6.</td>
<td>Stratigraphic column, Regina quadrangle</td>
<td>8</td>
</tr>
<tr>
<td>7.</td>
<td>Modal composition of felsic metavolcanic rocks and gneiss</td>
<td>10</td>
</tr>
<tr>
<td>8.</td>
<td>Photomicrograph of vermicular intergrowth radiating out from relict quartz phenocryst in felsic metavolcanic rock</td>
<td>13</td>
</tr>
<tr>
<td>9.</td>
<td>Dense, finely crystalline upper portion of the Mississippian Arroyo Peñasco Group</td>
<td>30</td>
</tr>
<tr>
<td>10.</td>
<td>Permian Yeso Formation showing bleached areas in upper portion</td>
<td>35</td>
</tr>
<tr>
<td>11.</td>
<td>White hummocky Todillo outcrops (Jt) and red, fine-grained sandstone of the Recapture Member of the Morrison Formation (Jm), offset by the Nacimiento fault and Faults 2A and 3A</td>
<td>41</td>
</tr>
<tr>
<td>12.</td>
<td>Kaolinite clasts and pebbles in the conglomeratic portion of the Jackpile Member of the Jurassic Morrison Formation</td>
<td>44</td>
</tr>
<tr>
<td>13.</td>
<td>Gray, carbonaceous shale at the contact between the Jurassic Morrison Formation and the Cretaceous Dakota Formation</td>
<td>46</td>
</tr>
<tr>
<td>Figure</td>
<td>Page</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>------</td>
<td></td>
</tr>
<tr>
<td>14. Northern Regina quadrangle; hogbacks formed on prominent sandstone in the Mancos Shale (Km), Point Lookout Sandstone, and La Ventana Tongue of the Cliff House Formation (Kmv)</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>15. Gray-black coal-bearing shale and carbonaceous sandstone of the Menefee Formation overlain by the sandstone of the La Ventana Tongue of the Cliff House Formation; Cretaceous Mesaverde Group</td>
<td>51</td>
<td></td>
</tr>
<tr>
<td>16. Pastel shales of the San Jose Formation</td>
<td>57</td>
<td></td>
</tr>
<tr>
<td>17. Conglomerate in the San Jose Formation; cobbles are limestone, probably derived from Cretaceous rocks</td>
<td>58</td>
<td></td>
</tr>
<tr>
<td>18. Generalized tectonic map, northwest New Mexico</td>
<td>61</td>
<td></td>
</tr>
<tr>
<td>19. Geology at Mahan Canyon, looking north</td>
<td>67</td>
<td></td>
</tr>
<tr>
<td>20. Diagrammatic structure sections showing development of the range-marginal structures in the eastern part of the Regina quadrangle</td>
<td>74</td>
<td></td>
</tr>
<tr>
<td>21. Strain diagrams showing forces during Laramide time and during Rio Grande rifting</td>
<td>77</td>
<td></td>
</tr>
<tr>
<td>22. Wrench zone along the northwest Nacimiento uplift</td>
<td>77</td>
<td></td>
</tr>
</tbody>
</table>
## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Petrographic data - felsic metavolcanic rocks</td>
<td>11</td>
</tr>
<tr>
<td>2. Petrographic data - mafic metavolcanic rocks</td>
<td>15</td>
</tr>
<tr>
<td>3. Petrographic data - gneiss</td>
<td>19</td>
</tr>
<tr>
<td>4. Petrographic data - aplite dikes</td>
<td>22</td>
</tr>
<tr>
<td>5. Petrographic data - mafic dikes</td>
<td>24</td>
</tr>
</tbody>
</table>
INTRODUCTION

The eastern half of the Regina quadrangle is located along the boundary between the northern Nacimiento uplift and the eastern San Juan Basin in north-central New Mexico. The Nacimiento uplift has been studied in detail further south (Woodward and others, 1972b), but no detailed investigation has been completed on the northern termination of this tectonic feature.

Previous work along the uplift has shown that this feature has been tectonically active at least three times in the past; during Pennsylvanian time, during the Laramide orogeny, and during Miocene and Pliocene time associated with Rio Grande rifting. The purpose of this project is to delineate the Nacimiento fault and related structures along the northwest side of the Nacimiento uplift and to identify the stratigraphic units present in the area. This information is used to determine the geologic history of this tectonically active area. In addition, Precambrian igneous and metamorphic rocks were examined to decipher the Precambrian events in the area.

Location and Accessibility

The mapped area is located in north-central New Mexico approximately 11 km (7 mi) north of Cuba, in Rio Arriba and Sandoval Counties. It includes approximately 80 km$^2$ (30 mi$^2$) of the eastern half of the Regina 7-1/2 minute quadrangle and is bounded on the north by 36° 15' N. latitude, on the south by 36° 7' 30" N. latitude, on the east by 106°
52° 30' W. longitude, and on the west by 106° 56' 50" W. longitude (Fig. 4). A majority of the area is located within the Santa Fe National Forest. About 3 sq mi is part of the San Pedro Parks Wilderness and the remainder is private land (Fig. 5).

Access to the area is available by State Road 96 which traverses the western and northern margins of the area. The Forest Service maintains dirt roads along San Jose Creek, La Jara Creek and Rio Gallina, and these, as well as a few poorly maintained logging roads, were used as access to some areas during dry weather (Fig. 5). Most places can be reached only by foot.

Physiography

The eastern half of the Regina quadrangle is divided into three physiographic areas. The northern third of the area is characterized by north- to northeast-trending hogbacks and strike valleys, with streams draining to the northeast. The western half of the southern part is mainly flat-topped terraces that have been dissected by westward flowing streams. The eastern half is the steep western margin of the northern Nacimiento Mountains, including a belt of north-trending ridges that mark the boundary between the northern Nacimiento Mountains and the terraces to the west.

The maximum elevation in the area is 3,120 m (10,240 ft) on a peak in the wilderness area and the minimum elevation is 2,210 m (7,240 ft) along Almagre Arroyo in the northwestern part of the area.
Figure 4. Location of the eastern part of the Regina quadrangle.
Figure 5. Detailed location map, eastern part of the Regina quadrangle.
The topographic relief within the Regina quadrangle varies; in the south the elevation may change as much as 275 m (900 ft) in less than 0.8 km (0.5 mi) but in the north the change is typically more gradual.

Methods

Field work was done from May to November, 1979, using a 1:24,000 scale U. S. Geological Survey topographic map as a base. Thin sections of the Precambrian rocks were examined using a polarizing microscope and modal percentages were based on visual estimates. Igneous rocks are classified according to the IUGS classification system (Streckeisen, 1967).

Previous Work

The first mapping in the Regina quadrangle was done on a reconnaissance basis by Renick (1931) who mapped the area as part of a U. S. Geological Survey report on groundwater resources of western Sandoval County; Wood and Northrop (1946) published a U. S. Geological Survey Oil and Gas Investigations Map that included the area.

On a more detailed basis, Hutson (1958) completed an M. S. thesis at the University of New Mexico that covered the northern portion of the area. Baltz (1967) published a U. S. Geological Survey Professional Paper concerned with the stratigraphy and regional tectonics of the Upper Cretaceous and Tertiary rocks along the eastern margin of the San
Juan Basin. Armstrong studied the Mississippian rocks in north-central New Mexico and published a map showing the location of Mississippian outcrops in the Regina quadrangle (Fitzsimmons and others, 1956). Santos and others (1975) evaluated the mineral resources of the San Pedro Parks Wilderness.

Acknowledgments

I thank Dr. Lee A. Woodward for suggesting the topic of this thesis and for assisting me throughout its preparation. Dr. Jon Callender and Dr. Bert Kudo were helpful in solving both academic and practical problems that occurred. Of the people who expressed an interest in this work I particularly appreciate the help of Steve Ristorcelli, Sandy Anderson and Randy Hicks.

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ROCK UNITS

Precambrian igneous and metamorphic rocks, and sedimentary rocks ranging in age from Mississippian to Tertiary are exposed along the northwestern Nacimiento uplift. The Precambrian rocks include granitic to granodioritic gneiss as well as metavolcanic and meta-sedimentary rocks. There are between 3,300-3,400 m (10,700 and 11,100 ft) of Mississippian to Tertiary rocks exposed. Quaternary deposits include alluvium, colluvium, and terrace and pediment deposits that reach a maximum thickness of 30 m (100 ft) (Fig. 6).

Precambrian Rocks

Rocks of Precambrian age are exposed in approximately 13-15 km² (5-6 mi²) in the southeastern Regina quadrangle in an area that is typified by rugged ridges and valleys with high relief, and thick vegetative and soil cover. Outcrops are small and discontinuous and in some areas float is the only information available.

The predominant Precambrian rock type is slightly- to well-foliated gneiss. Metavolcanic and metasedimentary rocks are found as xenoliths in the gneiss. These xenoliths represent the oldest rocks in the Regina quadrangle. Late-stage pegmatites, aplites, mafic dikes and quartz veins cut the older rocks. These metamorphic rocks have been subjected to at least one period of metamorphism, probably reaching the upper greenschist facies.

Mafic and felsic volcanic rocks occur as xenoliths in this area. Due to poor exposures in the Precambrian terrane, it is difficult to
<table>
<thead>
<tr>
<th>ERA</th>
<th>SYSTEM</th>
<th>SERIES</th>
<th>UNIT</th>
<th>THICKNESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quaternary</td>
<td>Cenozoic</td>
<td>Holocene and Pleistocene</td>
<td>Alluvium and Landslide Deposits</td>
<td>0-40 m (?)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0-125 ft (?)</td>
</tr>
<tr>
<td></td>
<td>Tertiary</td>
<td>Pliocene</td>
<td>Older Alluvium and Pediment Deposits</td>
<td>0-30 m (?)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0-100 ft (?)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Eocene</td>
<td>San Jose Formation</td>
<td>250-430 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>800-1400 ft</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Paleocene</td>
<td>Nacimiento Formation</td>
<td>300 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1000 ft</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Ojo Alamo Formation</td>
<td>30-40 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100-125 ft</td>
</tr>
<tr>
<td></td>
<td>Cretaceous</td>
<td>Upper</td>
<td>Kirtland Formation-Fruitland Shale</td>
<td>30 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100 ft</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lewis Shale</td>
<td>450 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1500 ft</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mesaverde Group</td>
<td>150 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>500 ft</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mancos Shale</td>
<td>600 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2000 ft</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lower</td>
<td>Dakota Formation</td>
<td>40 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>125 ft</td>
</tr>
<tr>
<td></td>
<td>Jurassic</td>
<td>Upper</td>
<td>Morrison Formation</td>
<td>230-250 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>750-800 ft</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Todillo Formation</td>
<td>30-45 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100-150 ft</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Entrada Sandstone</td>
<td>30-50 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>96-170 ft</td>
</tr>
<tr>
<td></td>
<td>Triassic</td>
<td>Upper</td>
<td>Upper Shale Member</td>
<td>170-180 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>560-600 ft</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Poleo Sandstone</td>
<td>25 m</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>80 ft</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Agua Zarca-Salitral Member</td>
<td>30 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100 ft</td>
</tr>
<tr>
<td></td>
<td>Permian</td>
<td>Lower</td>
<td>Yeso Formation</td>
<td>49-52 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>160-170 ft</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Abo Formation</td>
<td>490-550 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1600-1800 ft</td>
</tr>
<tr>
<td></td>
<td>Penns.</td>
<td>Upper</td>
<td>Madera Formation</td>
<td>0-540 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0-1775 ft</td>
</tr>
<tr>
<td></td>
<td>Miss.</td>
<td>Upper/Lower</td>
<td>Arroyo Peñasco</td>
<td>0-40 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0-120 ft</td>
</tr>
</tbody>
</table>

Figure 6. Stratigraphic column, Regina quadrangle.
estimate the exact sizes of the xenoliths, but in general their diameters probably range from centimeters to tens of meters. Although xenoliths are present throughout the area, they show a definite increase in abundance along the eastern and particularly the southeastern margins of the Precambrian terrane. One extensive exposure of mafic volcanic rock is present in the northern part of the area and is either a large xenolith or the side wall of the intrusion.

Felsic Metavolcanics

The composition of the felsic metavolcanics falls in the rhyodacite to dacite range (Fig. 7). They are pink, gray or tan and the average modal composition is quartz (33 percent), sodic plagioclase (29 percent), orthoclase (22 percent), chlorite and biotite (14 percent) and traces of hornblende, alteration minerals and accessory minerals. Detailed petrographic descriptions are found in Table 1.

Alteration products are not included in the average composition. The plagioclase is commonly altered in varying degrees to a fine-grained assemblage of epidote + sericite + chlorite. The amount of alteration varies, as some plagioclase remains relatively fresh but others are recognized only by crystal shape or relict twinning. Some of the large plagioclase grains may be porphyroblasts which formed as a contact effect during emplacement of the granitic magma. The orthoclase is typically kaolinized. Hornblende is altered to biotite, and both are altered to chlorite ± magnetite.
Figure 7. Modal composition of felsic metavolcanic rocks (●) and gneiss (x). Q=quartz, A=alkali feldspar, P=plagioclase >An$_{05}$ (after Streickeisen, 1967).
Table 1. Petrographic data—felsic metavolcanic rocks.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>%</th>
<th>Color</th>
<th>Habit</th>
<th>Size (mm)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>quartz</td>
<td>33</td>
<td>colorless</td>
<td>xenomorphic</td>
<td>polycrystalline aggregates 1.0-3.0; grains 0.1-0.5</td>
<td>polycrystalline aggregates may show suturing, embayment (?)</td>
</tr>
<tr>
<td>plagioclase</td>
<td>29</td>
<td>colorless</td>
<td>idiomorphic to hyp-idiomorphic</td>
<td>porphyroblasts 2.0; grains 0.1-0.75</td>
<td>altered to fine-grained aggregate of chlorite + epidote + sericite An4-8 maximum extinction angle 15°-18°</td>
</tr>
<tr>
<td>orthoclase</td>
<td>22</td>
<td>colorless</td>
<td>xenomorphic</td>
<td>0.1-0.75</td>
<td>kaolinitized</td>
</tr>
<tr>
<td>biotite</td>
<td>8</td>
<td>pale yellow x=green brown z=green brown</td>
<td>hyp-idiomorphic</td>
<td>aggregates 1.0-2.0; grains 0.1-0.5</td>
<td>replaces hornblende grains rimmed by opaques</td>
</tr>
<tr>
<td>chlorite</td>
<td>6</td>
<td>colorless x=green z=green</td>
<td>hyp-idiomorphic</td>
<td>0.1-0.5</td>
<td>grains with associated opaques</td>
</tr>
<tr>
<td>hornblende</td>
<td>1</td>
<td>pale yellow x=green y=green z=blue-green</td>
<td>hyp-idiomorphic</td>
<td>0.075-0.5</td>
<td>altered to biotite and chlorite</td>
</tr>
<tr>
<td>epidote</td>
<td>tr</td>
<td>colorless</td>
<td>xenomorphic</td>
<td>0.1-0.02</td>
<td></td>
</tr>
<tr>
<td>apatite</td>
<td>tr</td>
<td>colorless</td>
<td>hyp-idiomorphic</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>magnetite</td>
<td>tr</td>
<td>opaque</td>
<td>xenomorphic</td>
<td>0.1-1.5</td>
<td></td>
</tr>
<tr>
<td>muscovite</td>
<td>tr</td>
<td>colorless</td>
<td>hyp-idiomorphic</td>
<td>grains 0.05</td>
<td>aggregates 2.0</td>
</tr>
<tr>
<td>garnet</td>
<td>tr</td>
<td>red</td>
<td>xenomorphic</td>
<td>grains 0.25</td>
<td>one sample only</td>
</tr>
</tbody>
</table>
The felsic metavolcanics may show foliation, defined by the parallel arrangement of chlorite or biotite grains, but foliation may be very poorly developed or absent. This may be due either to a lack of platy minerals or the absence of strong penetrative deformation.

Large grains of quartz or rarely feldspar are found in a groundmass that is a fine-grained aggregate of quartz, orthoclase, plagioclase, biotite, chlorite and hornblende. The large quartz grains may have square or round outlines and are typically polycrystalline grains, sometimes with slightly sutured boundaries.

These large quartz grains may be relict phenocrysts that have undergone partial recrystallization, a phenomenon that is in agreement with Spry's (1969) observation that "igneous crystals are polygonized and are partially or wholly recrystallized" during metamorphism. In addition, these relict quartz phenocrysts are sometimes slightly embayed, indicating relict volcanic texture. The fact that the grains may have square outlines is also evidence of a volcanic origin (Moorhouse, 1970).

One unusual textural feature present in some of the felsic metavolcanics are granophyric intergrowths. These intergrowths of quartz and either orthoclase or rarely plagioclase are present in the groundmass, either as randomly oriented intergrowths or as radiating vermicular intergrowths. In two of the samples vermicular intergrowths of quartz and orthoclase are present as rims that radiate out from relict quartz phenocrysts (Fig. 8).

The origin of these vermicular intergrowths is not entirely understood. I believe that the intergrowths in the groundmass may
Figure 8. Photomicrograph of vermicular intergrowth radiating out from relict quartz phenocryst in felsic metavolcanic rock (PÇf). Long dimension of photographic is 2.05 mm, crossed nichols.
have been glissy matrix that devitrified to form spherulites that later were recrystallized during metamorphism. The radiating rims around the relict quartz phenocrysts represent granophyric rims that were later recrystallized. Spherulitic rims similar to those found in these rocks are also present in Precambrian metavolcanic rocks at Matagami, Quebec (Moorhouse, 1970). Spry (1969, p. 203) indicated that glass recrystallizes to a "granoblastic quartz-feldspar or feldspar aggregate" and that symplectites may be produced during metamorphism.

Mafic Metavolcanics

Metavolcanic rocks of intermediate to mafic composition are most common in the northern part of the Precambrian terrane, and form more extensive exposures than the other metavolcanic and metasedimentary rocks, although they are also present as xenoliths elsewhere (Fig. 1).

The original compositions of these rocks are difficult to determine due to extensive alteration. These rocks are dark green or gray in hand specimen, and are fine grained and poorly to moderately foliated. They are composed of chlorite (50 percent), plagioclase (25 percent), quartz (10 percent), calcite (10 percent), pyrite (7 percent) and epidote (7 percent). Foliation is defined by the partial alignment of chlorite. Petrographic data is included in Table 2.

The chlorite in these rocks probably replaced original igneous pyroxene. Whether hornblende was an intermediate product, formed from
<table>
<thead>
<tr>
<th>Mineral</th>
<th>%</th>
<th>Color</th>
<th>Habit</th>
<th>Size (mm)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>chlorite</td>
<td>40</td>
<td>x=colorless</td>
<td>hyp-</td>
<td>1.5-0.75</td>
<td>replaces a mineral with amphibole (?) form</td>
</tr>
<tr>
<td></td>
<td>65</td>
<td>z=pale green</td>
<td>idiomorphic</td>
<td></td>
<td>forms a felted mat in groundmass</td>
</tr>
<tr>
<td>plagioclase</td>
<td>0</td>
<td>colorless</td>
<td>idiomorphic</td>
<td>1.75-0.25</td>
<td>partially to completely replaced by a fine-grained aggregate of chlorite +</td>
</tr>
<tr>
<td></td>
<td>33</td>
<td></td>
<td>to hyp-</td>
<td></td>
<td>sericite + epidote + calcite</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>idiomorphic</td>
<td></td>
<td>$\theta$, maximum extinction angle $= 14^\circ$</td>
</tr>
<tr>
<td>calcite</td>
<td>0</td>
<td>colorless</td>
<td>xenomorphic</td>
<td>0.2</td>
<td>occurs as both veins and as disseminations</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>quartz</td>
<td>5</td>
<td>colorless</td>
<td>xenomorphic</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>15</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pyrite</td>
<td>5</td>
<td>opaque</td>
<td>hyp-</td>
<td>0.1-0.3</td>
<td>skeletal forms occur</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td></td>
<td>idiomorphic</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>xenomorphic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>epidote</td>
<td>0</td>
<td>colorless</td>
<td>xenomorphic</td>
<td>0.075-0.1</td>
<td>fine-grained aggregate</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>biotite</td>
<td>tr</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>muscovite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
from the pyroxene during metamorphism and later destroyed, is not known.

Sodic plagioclase forms randomly oriented idiomorphic to hypidiomorphic grains. The absence of plagioclase in one specimen is due to the replacement of this mineral by fine-grained clay minerals, calcite and epidote. In hand specimen plagioclase relics are present, and plagioclase originally composed approximately 15 percent of the rock.

The abundance of calcite in one sample is the result of weathering of the overlying Mississippian and Pennsylvanian limestone. Quartz is found as small xenomorphic grains in the groundmass of these rocks, and the pyrite forms hypidiomorphic to skeletal crystals that are disseminated throughout the rock. The epidote is present as fine-grained aggregates and may either be a product of metamorphism or later alteration.

Microscopically these mafic rocks show blastophitic textures. This relict texture is represented by randomly oriented idiomorphic to hypidiomorphic plagioclase laths in an unoriented felted mass of chlorite. The composition and texture of this unit suggest that these rocks were originally intermediate to mafic flows or subvolcanic intrusives.

Metasedimentary Rocks

Metasedimentary rocks are not common in the Regina quadrangle and were identified mainly on the basis of high quartz content and texture. Only three thin sections were made of metasedimentary rocks and all
three are different, both compositionally and texturally; they are briefly described below.

A sample from the southern part of the area is composed of predominantly quartz (50 percent), with microcline (25 percent), altered plagioclase (15 percent), blue-green hornblende (10 percent), brown-green biotite (5 percent), and minor epidote and magnetite. It is medium-gray, fine grained, and foliation is defined by the alignment of hornblende and biotite and by the slight elongation of quartz grains. The original sedimentary rock may have been dolomitic, feldspathic graywacke or a dolomitic, lithic arkose.

A metasedimentary xenolith in the central part of the Precambrian terrane is composed of 60 percent quartz with 20 percent plagioclase, 15 percent orthoclase and 5 percent biotite. It is moderately foliated and has a fine-grained granoblastic groundmass with larger (up to 4.0 mm) elongate grains of polycrystalline quartz, quartz and feldspar, or quartz, feldspar and biotite. These larger grains all show the same orientation and may represent rock and mineral fragments that were incorporated into the rock during sedimentation, forming a conglomeratic, lithic arkose. Idiomorphic plagioclase grains, like those found in the felsic metavolcanics, may have formed as a reaction between the xenoliths and the intrusion.

In the northern part of the Precambrian area there is float of a rock type with a sedimentary origin. This rock is composed of 50 percent quartz, 25 percent chlorite, 15 percent muscovite and 10 percent
magnetite and is fine grained and has a mylonitic texture. When plotted on an A'FK diagram the composition of this rock falls in the range of graywacke (Winkler, 1976). The high percentage of quartz, which cannot be represented on a A'FK diagram, indicates that this rock may have been a quartz wacke.

Gneiss

The predominant Precambrian rock type in the Regina quadrangle is poorly to well-foliated gneiss that is granitic to granodioritic in composition. Alteration of the feldspars has made their identification, as well as the classification of the rock, difficult in some cases. The majority of the samples fall along the granite-granodiorite boundary as defined by Streckeisen (1967), but variations include more granitic rocks, as well as tonalite (Fig. 7).

The gneiss is mainly pink or pink-gray and forms outcrops that are fairly common but not extensive. Contacts with the xenoliths are typically covered. The average modal composition of the gneiss is quartz (34 percent), plagioclase (30 percent), orthoclase (19 percent), biotite (7 percent), hornblende (5 percent) and chlorite (3 percent). See Table 3 for detailed information on petrography. Quartz occurs in the gneiss both as polycrystalline aggregates with slightly sutured polygonal grains locally with strained extinction, or as single xenomorphic grains.
Table 3. Petrographic data—gneiss.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>% Color</th>
<th>Habit</th>
<th>Size (mm)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>quartz</td>
<td>34</td>
<td>colorless, xenomorphic</td>
<td>polycrystalline aggregates 2.0, grains 1.25-0.05</td>
<td>occurs as polycrystalline grains with slightly sutured boundaries or as single grains, sometimes with strained extinction</td>
</tr>
<tr>
<td>plagioclase</td>
<td>30</td>
<td>colorless, Idiomorphic-xenomorphic</td>
<td>porphyroblasts-2.0-3.0, grains 0.9-0.3</td>
<td>pervasively altered to fine-grained aggregate of sericite + chlorite + epidote too altered for An determination</td>
</tr>
<tr>
<td>orthoclase</td>
<td>19</td>
<td>colorless, xenomorphic</td>
<td>1.0-0.1</td>
<td>kaolnized</td>
</tr>
<tr>
<td>biotite</td>
<td>8</td>
<td>pale yellow, pale green, brown, green-brown</td>
<td>aggregates-1.0-2.0, grains 0.5-0.2</td>
<td>pseudomorphic after hornblende with opaques partially altered chlorite</td>
</tr>
<tr>
<td>hornblende</td>
<td>5</td>
<td>yellow-green, green</td>
<td>0.2-0.1</td>
<td>partially altered to biotite and chlorite with associated opaques</td>
</tr>
<tr>
<td>chlorite</td>
<td>3</td>
<td>colorless, green</td>
<td>0.75-0.2</td>
<td></td>
</tr>
<tr>
<td>epidote</td>
<td>tr</td>
<td>colorless, xenomorphic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>opaque</td>
<td>tr</td>
<td>opaque, xenomorphic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>apatite</td>
<td>tr</td>
<td>colorless, hyp-Idiomorphic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>zircon</td>
<td>tr</td>
<td>colorless, hyp-Idiomorphic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>sphene</td>
<td>tr</td>
<td>colorless, hyp-Idiomorphic</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The plagioclase is now a fine-grained aggregate of sericite +
epidote + chlorite and its original composition is unknown. Plagioclase
is found both as xenomorphic to hypidiomorphic grains and as idiomorphic
porphyroblasts that are a result of contact effects with the xenoliths.
Orthoclase is altered in part to fine-grained clay, probably kaolinite,
as well as epidote, chlorite and sericite.

The hornblende is partially replaced by biotite, which, in turn,
is partially replaced by chlorite. Biotite and chlorite may form
pseudomorphic grains after hornblende, with opaque minerals outlining
grain boundaries and relict clevage traces.

Foliation in the gneiss is poorly to well developed. Where
foliation is poor, only a vague mineral banding is observed. In moderately
well foliated rocks, biotite and plagioclase grains are aligned, and
well foliated specimens show mineral segregations into light and dark
colored bands. Foliation is best developed in the southeastern Regina
quadrangle, where it is inconsistent in overall trend.

The gneiss is medium- to coarse-grained and composed of an
interlocking framework of xenomorphic to hypidiomorphic grains with an
interlobate to polygonal texture. Where foliation is poorly developed
a sericate to inequigranular granoblastic texture dominates. These
recrystallization-type textures are evidence that the gneiss has been
metamorphosed and is not just a granite that was foliated during
emplacement (Turner and Verhoogen, 1960). Recrystallization associated
with metamorphism tends to polygonize igneous crystals, a phenomena
observed in these samples, particularly in quartz grains. Further postcrystallization deformation has resulted in slightly sutured grain boundaries, rare kink bands in the biotite, and locally deformed plagioclase grains.

Dikes and Veins

The last intrusive event to occur in the Regina quadrangle is the emplacement of both aplite and mafic dikes, and quartz and pegmatite veins. The massive quartz or quartz and microcline veins are distributed throughout the gneiss and will not be discussed in further detail. The aplite and mafic dikes cut the gneiss also, and due to poor exposure, data concerning thickness, lateral extent and in some cases, trend, could not always be obtained. The leucogranodiorite noted by McLelland (Woodward and others, 1977b) in the Regina quadrangle was not located. The area where it had been located by McLelland has numerous thick aplite dikes that are granitic in composition.

Aplite dikes—

Fine-grained pink aplite dikes are present primarily in the central portion of the Precambrian terrane. The aplites are composed of quartz, orthoclase, microcline, plagioclase and biotite and are granitic in composition (Table 4). Their texture is fine-grained granoblastic and saccharoidal. Chill margins have been observed at the aplite-gneiss contact. These rocks may have been slightly affected

21
Table 4. Petrographic data—aplite dikes.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>%</th>
<th>Color</th>
<th>Habit</th>
<th>Size (mm)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>quartz</td>
<td>37</td>
<td>colorless</td>
<td>xenomorphic</td>
<td>0.3-0.03</td>
<td></td>
</tr>
<tr>
<td>orthoclase</td>
<td>45</td>
<td>colorless</td>
<td>xenomorphic</td>
<td>0.3-0.03</td>
<td>slightly kaolinized</td>
</tr>
<tr>
<td>microcline</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>plagioclase</td>
<td>13</td>
<td>colorless</td>
<td>xenomorphic</td>
<td>0.3-0.03</td>
<td>rarely twinned; altered to sericite +</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>chlorite + epidote</td>
</tr>
<tr>
<td>biotite</td>
<td>5</td>
<td>x=colorless</td>
<td>hypidiomorphic</td>
<td>0.3-0.03</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>z=red-brown</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>epidote</td>
<td>tr</td>
<td>colorless</td>
<td>xenomorphic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>chlorite</td>
<td>tr</td>
<td>pale green</td>
<td>hypidiomorphic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>muscovite</td>
<td>tr</td>
<td>colorless</td>
<td>hypidiomorphic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>opaque</td>
<td>tr</td>
<td>opaque</td>
<td>xenomorphic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>sericite</td>
<td>tr</td>
<td>colorless</td>
<td>hypidiomorphic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>apatite</td>
<td>tr</td>
<td>colorless</td>
<td>hypidiomorphic</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
by metamorphism as biotite may show a preferred orientation. Interlobate, recrystallized grain boundaries are also observed.

Mafic dikes --

Mafic dikes also cut the older Precambrian rocks. These rocks are dark green in hand specimen and are composed mainly of hornblende and plagioclase with minor quartz, pyrite and magnetite (Table 5). The hornblende in these mafic dikes occurs as unoriented laths that are partially replaced by chlorite and magnetite, particularly along cleavages. The plagioclase is andesine and is partially replaced by fine-grained sericite, epidote and chlorite. Quartz occurs as small interstitial grains. The pyrite is found as euhedral or skeletal grains.

These rocks are idiomorphic to hypidiomorphic granular and are not foliated. This lack of metamorphic texture indicates that the chlorite and epidote in these rocks are not products of metamorphism.

Age

The Precambrian rocks in the northern Nacimiento Mountains are Proterozoic in age. Brookins (1974) analyzed a metavolcanic rock from the Nacimiento Peak quadrangle, southeast of the Regina quadrangle, using the Rb-Sr method and obtained a date of 1,800 ± 50 m.y. A 1,840 ± 170 m.y. date, also by Rb-Sr, was obtained on a leucogranodiorite in the Regina quadrangle. My field work in this area has failed to locate this leucogranodiorite and I believe an aplite dike may have been dated instead. If this is the case, there seems to be
Table 5. Petrographic data---mafic dikes

<table>
<thead>
<tr>
<th>Mineral</th>
<th>%</th>
<th>Color</th>
<th>Habit</th>
<th>Size (mm)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>hornblende</td>
<td>55-</td>
<td>x=pale yellow</td>
<td>euhedral</td>
<td>1.5-0.2</td>
<td>may be partially altered to chlorite + epidote + magnetite maximum extinction angle = 22°</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>y=green</td>
<td>subhedral</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>z=blue-green</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>plagioclase</td>
<td>15-</td>
<td>colorless</td>
<td>euhedral</td>
<td>1.0-0.25</td>
<td>An, maximum extinction angle = 24° altered to sericite + chlorite + epidote</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td></td>
<td>subhedral</td>
<td></td>
<td></td>
</tr>
<tr>
<td>quartz</td>
<td>5</td>
<td>colorless</td>
<td>anhedral</td>
<td>0.1-0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pyrite</td>
<td>5</td>
<td>none</td>
<td>subhedral</td>
<td>0.2-0.07</td>
<td>pyrite occurs as skeletal grains magnetite occurs as fine disseminations</td>
</tr>
<tr>
<td>magnetite</td>
<td></td>
<td></td>
<td>anhedral</td>
<td></td>
<td></td>
</tr>
<tr>
<td>chlorite</td>
<td>0-</td>
<td>x=colorless</td>
<td>subhedral</td>
<td>0.25</td>
<td>alteration of hornblende</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>z=green</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>epidote</td>
<td>tr</td>
<td>colorless</td>
<td>anhedral</td>
<td>0.2-0.02</td>
<td>alteration of hornblende and plagioclase</td>
</tr>
<tr>
<td>sericite</td>
<td>tr</td>
<td>colorless</td>
<td>subhedral</td>
<td>0.1-0.03</td>
<td>alteration of plagioclase</td>
</tr>
</tbody>
</table>
an error in these dates since the oldest date was obtained on a rock which field relations indicate as being younger.

An unpublished U-Pb analysis on zircon from the rapikivi quartz monzonite in the southern part of the San Pedro Parks Wilderness yields a date of 1,730 ± 20 m.y. This date was done by Leon T. Silver at the California Institute of Technology, and since this quartz monzonite is thought to be younger than the Precambrian rocks in the Regina quadrangle, it provides a minimum age for those rocks (L. A. Woodward, pers. comm. 1980).

Metamorphism

Previous studies of the Precambrian rocks of the Sierra Nacimiento have shown that a period of regional metamorphism affected the older volcanic-sedimentary terrane prior to the period of granitic to tonolitic intrusion (Reed, 1971; Woodward and others, 1974c). Reed (1971) cited evidence for a second, younger period of regional metamorphism in the southern Sierra Nacimiento, while in the northern Nacimiento Mountains the only other Precambrian deformational event was a period of cataclasis (Woodward and others, 1974c).

In the Regina quadrangle petrographic evidence suggests that all but the youngest Precambrian rocks (i.e., the mafic dikes) have been metamorphosed, but there is no definitive evidence, such as two foliation directions or indisputable prograde or retrograde reactions in the xenoliths, that two periods of metamorphism have occurred. Some indirect evidence for only one period of metamorphism, post intrusion, include:
1. Foliation in the xenoliths has the same trend as foliation in the gneiss.

2. Foliation in the xenoliths seems to be more well developed in areas where foliation in the gneiss is more well developed. This may imply that the same forces caused the foliation in both.

3. The felsic metavolcanics and the gneiss have similar compositions, indicating that they may be related in time as well as in space.

The determination of metamorphic grade in the Precambrian rocks is restricted by certain facts. Plagioclase has been replaced by sericite, epidote and chlorite to such an extent that An content, a useful metamorphic indicator, cannot be precisely determined. The overwhelming mineral assemblage seen in this area is quartz, plagioclase and orthoclase, which is an assemblage that is not overly sensitive to mineralogical changes, especially during low to medium grade metamorphism. The assemblage chlorite + epidote is pervasive in a majority of the rocks, but it cannot be proven that this is a metamorphic assemblage and not the result of hydrothermal alteration.

Metamorphism in the Regina quadrangle probably reached the upper greenschist facies. The evidence for this grade metamorphism is
based on the occurrence of sodic plagioclase, hornblende, garnet, ± chlorite and epidote in the metavolcanic rocks. These minerals are common constituents of upper greenschist facies metamorphism (Winkler, 1976; Miyashiro, 1973). Although garnet is a minor constituent only, it is present also in metavolcanic rocks just to the east of the area.

Structure and Mechanisms of Emplacement

In general the foliation in the metamorphic rocks appears to trend north to northwest, but where foliation is best developed, in the southern part of the Precambrian terrane, it is very inconsistent. Foliation here tends to change rapidly along strike over short distances. But this general north- to northwest-trend is in agreement with results elsewhere in the northern Nacimiento Mountains (Woodward and others, 1977b).

Examination of the felsic metavolcanics and the gneiss shows a similarity in composition. This suggests that these rocks are genetically related and that the parent of the gneiss intruded its own volcanic pile. Such occurrences have been noted in younger rocks such as the Boulder Batholith and Elkhorn Volcanics (Hamilton and Myers, 1967).

Intrusion of the parent of the gneiss is probably partly the result of emplacement by piecemeal stoping. This is a process in which the magma surges upward along joints or fractures during emplacement, causing large blocks of the country rock to cave into the magma chamber and sink or be assimilated (Turner and Verhoogen, 1960; Hyndman, 1972).
The evidence for emplacement by this mechanism is the presence of inclusions of metavolcanic and metasedimentary rocks. Variation in composition of the gneiss from granite to tonolite is possibly a result of assimilation. There is no field evidence that the gneiss is more mafic adjacent to mafic inclusions, but in one thin section a small (<3.0 mm) hornblende-rich xenolith was observed in a quartz diorite gneiss with an unusually high (25 percent) hornblende content.

Reed (1971) cited evidence for both assimilation and forceful intrusion of the parent of the quartz monzonite gneiss in the southern Sierra Nacimiento. No evidence for forceful intrusion, such as dilation, was observed in the Regina quadrangle, as the margins of the pluton are not exposed.

Mississippian System

Arroyo Peñasco Group

The Arroyo Peñasco Group was named by Armstrong (1955) with its type locality at Peñasco and Piños Canyons in the southern Sierra Nacimiento. Prior to that time, Read and others (1944) and Wood and Northrop (1946) recognized the distinctness of this unit, but lacking paleontological evidence, included it in the Pennsylvanian Sandia Formation.

The Arroyo Peñasco caps the highest ridges in the east-central portion of the Regina quadrangle and reaches a maximum thickness of approximately 40 m (120 ft), with the upper portion of the section eroded. It rests unconformably on Precambrian rocks and is
unconformably overlain by the Pennsylvanian Madera Formation. The lower 1.5 m (5 ft) of this unit consists of white, medium- to coarse-grained, locally conglomeratic quartz sandstone that is overlain by 3 m (10 ft) of poorly exposed, thin-bedded sandstone, shale, and limestone. The limestone beds in this portion reach a maximum thickness of 15 cm and commonly show cranulations. Above this is approximately 8 m (25 ft) of dense, tan to gray, finely crystalline cherty limestone that occurs in beds 0.3 to 0.6 m (1 to 2 ft) thick. The uppermost portion of this formation is about 10 m (30 ft) of dense, gray, finely crystalline limestone with white chert (Fig. 9). From his work here and elsewhere in north-central New Mexico, Armstrong (1967) recognized this sequence as representing an initial transgressive phase of deposition followed by three carbonate depositional cycles.

Exposures of the Arroyo Peñasco Group are found in the Sierra Nacimiento, the Jemez Mountains, the Sandia Mountains, and the Sangre de Cristo Mountains. These isolated outcrops represent downfaulted blocks and erosional remnants of strata which once covered northern New Mexico (Fitzsimmons and others, 1956). In the southern Nacimiento and the Jemez Mountains the Arroyo Peñasco is overlain by the Upper Mississippian or Lower Pennsylvanian Log Springs Formation, the Pennsylvanian Osha Canyon Formation, and the Pennsylvanian Sandia Formation. In the northern Nacimiento Mountains there is evidence that the Log Springs Formation was once present; hematite nodules are found scattered in float capping the ridge in sec. 1, T. 22 N., R. 1 W. The Osha Canyon and Sandia Formations are absent in the northern Nacimiento
Figure 9. Dense, finely crystalline upper portion of the Mississippian Arroyo Peñasco Group. Upper beds are approximately 0.3 m (1.0 ft) thick.
due to uplift along the Peñasco axis during Late Mississippian or Early Pennsylvanian time (DuChene, 1974).

There has been argument over the age of the Arroyo Peñasco. Fossils examined by Gordon (Fitzsimmons and others, 1956) and by Armstrong (1974) indicate a late Osage to early Meramec age for this unit. In 1960, Baltz and Read subdivided the Arroyo Peñasco into two units, the Espiritu Santu Formation which included the lower clastics, and the Tererro Formation. On the basis of lithology these formations were correlated with rocks in southern Colorado and assigned ages of Devonian (?) and Kinderhook to Meramec, respectively. This classification has been used extensively in northern New Mexico, but Armstrong and Holcomb (1967) pointed out the existence of Late Osage and Early Meramec fossils in the so-called Devonian rocks and have proposed that Arroyo Peñasco still be used as the group name and Espiritu Santu and Tererro used as formation names.

Pennsylvanian System

Madera Formation

The Pennsylvanian Madera Formation was named by Keyes (1903) for localities in the Sandia Mountains, where it has been divided into two members, the lower Gray Limestone Member and the upper Arkosic Member (Wood and Northrop, 1946). Wood and Northrop used these members in the Nacimiento Mountains, but I could not distinguish these two members and therefore mapped the Madera as one unit. In the northern Nacimiento
Mountains the Madera rests unconformably on Precambrian rocks, except at the few localities where it unconformably overlies the Arroyo Peñasco Group. The contact with the overlying Abo Formation is gradational, the boundary being defined as the top of the stratigraphically highest thick fossiliferous limestone bed. Hutson (1958) noted the presence of an angular unconformity between the Madera and the Abo in sec. 30, T. 23 N., R. 1 E., but I believe that this is a pinch-out of certain limestone beds and not an erosional unconformity.

The Madera Formation is composed of 540 m (1,775 ft) of interbedded gray limestone, arkosic sandstone, and red shale. At its base is about 3 m (10 ft) of well indurated, white to red-brown, locally arkosic, quartz sandstone that is typically medium- to coarse-grained and locally conglomeratic. Above this basal sandstone, limestone is found in units up to 5 m (15 ft) thick that are made up of beds 15 cm to 30 cm thick. It is typically medium-gray to pink-brown, coarsely crystalline and locally contains abundant fossils (crinoid stems, brachiopods, and bryozoans), angular pink feldspar grains, and white to gray nodular chert. At one locality the limestone contains abundant reworked algal concretions.

Interbedded with this limestone is sandstone that is white to red, poorly cemented, moderately sorted, and medium grained. It is typically arkosic and locally clay and biotite are found in the matrix. Red shale is found interbedded with the limestone and the sandstone and is a slope-former. Stratigraphically higher in the Madera the number of
limestone beds decreases and the amount of arkosic sandstone and shale increases, forming a gradational contact with the overlying Abo Formation.

The Madera Formation is the result of transgression of the Pennsylvanian sea over the Peñasco uplift. Deposition occurred in a shallow marine and locally high energy tidal flat environment.

Permian System

Abo Formation

The continental deposits of the Abo Formation were named by Lee (1909) at the type locality in Abo Canyon at the south end of the Manzano Mountains. In the Regina quadrangle the Abo forms a gradational contact with the Madera Formation at the north end of the Nacimiento uplift and along the western margin where the Madera is absent, the Abo rests unconformably on Precambrian rocks.

The primary lithology of the Abo Formation is red, silty shale. Interbedded with this shale is lenticular, cross-bedded, thick- to thin-bedded, medium- to coarse-grained arkosic sandstone. This red-maroon to buff sandstone is moderately sorted, subangular to rounded and composed of quartz and feldspar grains up to 1.25 cm in diameter, and minor amounts of mafic grains. Conglomeratic layers are also present in the Abo Formation and may contain rounded pebbles of Precambrian quartzite which outline channels and foreset beds. Thin, discontinuous, non-fossiliferous limestone beds are present near the contact with the Madera Formation.
The Abo Formation is the result of regression of the Pennsylvanian sea and the gradual dominance of continental sedimentation. Where the Abo has not been faulted its thickness has been measured as between 490 m (1,600 ft) and 550 m (1,800 ft).

Yeso Formation

The Yeso Formation was named in 1909 by Lee for rocks exposed at Mesa del Yeso, New Mexico. Wood and Northrop (1946) divided the Yeso into two members, the lower Meseta Blanca and the upper San Ysidro, but due to poor exposures these members were not differentiated in the Regina quadrangle.

The contact between the Yeso Formation and the underlying Abo Formation was chosen on the basis of two criteria; the occurrence of continuous non-feldspathic, even-grained sandstone beds, and the color change from maroon-red in the Abo to orange-red in the Yeso. The thickness of the Yeso Formation is estimated to be 49 m (160 ft) to 52 m (170 ft). The location of the Abo-Yeso contact in the Regina quadrangle, as well as the estimate of thickness, may be complicated by faulting.

The Yeso Formation is composed of thick-bedded, cross-bedded sandstone with thin interbeds of red shale. This sandstone is well sorted, fine grained and red-orange, except near the upper contact where white bleached areas become common (Fig. 10). Coarse-grained beds with abundant clay matrix are locally present.

Conventionally, north of 36° north latitude the Abo and Yeso Formations have been mapped together as the Cutler Formation, but
Figure 10. Permian Yeso Formation (Py) showing bleached areas in upper portion.
in the Regina quadrangle, as well as in the Gallina quadrangle to the east (Gibson, 1975), the Abo and the Yeso are two distinct units and are mapped as such.

The Yeso Formation was formed during a tectonically quiescent period, along a coastal plain. The bleached areas at the top of this formation can be attributed to sub-aerial erosion prior to deposition of Triassic sediments.

Triassic System

Chinle Formation

In 1917 Gregory named the Chinle Formation for exposures in the Chinle Valley in northeastern Arizona. In 1946, Wood and Northrop subdivided the Chinle in the Nacimiento area into four members; the lower Agua Zarca Sandstone, the Salitral Shale, the Poleo Sandstone Lentil, and the Upper Shale Member.

The Agua Zarca Member has been named for strata exposed at Agua Zarca Creek in Rio Arriba County, New Mexico, and the Salitral for exposures at Salitral Creek, also in Rio Arriba County (Wood and Northrop, 1946). These two members have been mapped as one unit in the Regina quadrangle due to the intertonguing relationship between them. The maximum thickness of this unit is 30 m (100 ft).

The Agua Zarca-Salitral rests unconformably on the Yeso Formation, and is composed predominantly of purple-maroon shale and siltstone with nodular limestone. Discontinuous lenses within the shale are
thick-bedded, fine-grained to conglomeratic, white to buff quartz sandstone. The sand grains are poorly sorted, angular to subrounded and may form crossbeds.

Stewart and others (1972) and Gibson (1975) have hypothesized that the Agua Zarca-Salitreral unit represents alluvial plain and fan deposits. The cross-bedded sandstones are alluvial fan channel deposits which carried sediment away from the Triassic Brazos uplift. Work by Kurtz and Anderson (1980) shows that the Agua Zarca Sandstone was deposited in a high energy braided stream environment. These Agua Zarca sandstones are interlayered with the alluvial plain deposits of the Salitreral Shale.

The Poleo Sandstone Lentil overlies and forms a sharp erosional boundary with the Agua Zarca-Salitreral Member. This unit caps a ridge in the northern part of the map area and forms a fin in the southern part, reaching a thickness of 25 m (80 ft). The major lithology in the Poleo Sandstone is yellowish-gray, fine-grained, moderately sorted, cross-bedded micaceous quartz sandstone. It is found in beds up to 1 m (3 ft) thick, and variation in the degree of induration results in variable outcrop appearance. The Poleo is locally conglomeratic, containing gray, orange and red chert pebbles. Kurtz and Anderson (1980) stated that the Poleo Sandstone is the result of sedimentation in a braided stream that was originally a high energy environment that became increasingly more low energy with time. This is substantiated by the cross-bedded, poorly sorted micaceous nature of the lentil in which conglomeratic beds are more abundant in the lower portion. Also during deposition of the Poleo the sediment source shifted from the
Brazos uplift to the south and east. This possibly reflects a sediment source in the Pedernal Highland or in east Texas (Kurtz and Anderson, 1980).

Red, green and purple shale of the Upper Member of the Chinle gradationally overlies the Poleo Sandstone Lentil. Thin-bedded siltstone and argillaceous sandstone are interbedded with the shale. A complete section of the Upper Member is not present in the Regina quadrangle and therefore the thickness could not be measured. Gibson (1975) reports 170 m (560 ft) in the Gallina quadrangle to the east, and Anderson (1970) states that 180 m (600 ft) is present in the Cuba quadrangle to the south. The thickness probably falls between these two in the Regina quadrangle. The Upper Member is the result of deposition on a diminished paleoslope, in a floodplain or marshland environment (Kurtz and Anderson, 1980).

Jurassic System

Entrada Sandstone

The Jurassic Entrada Sandstone was named by Gilluly and Reeside (1928) for exposures at Entrada Point in the San Rafael Swell area of Utah. In the Gallina quadrangle, Gibson (1975) divided the Entrada into four members. At all locations in the Regina quadrangle the Entrada has a fault as its lower contact and exposures are poor, being a valley- or slope-forming unit. For these reasons I mapped the Entrada as one unit.
The Entrada Sandstone rests disconformably on the Chinle Formation and is estimated to be 45-50 m (150-170 ft) thick in the Gallina quadrangle (Gibson, 1975) and 30 m (96 ft) thick in the Cuba quadrangle (Anderson, 1970). In the Regina quadrangle the thickness probably falls in this range.

The Entrada Sandstone is composed of fine-grained, cross-bedded, quartz sandstone. At the stratigraphically lowest exposures it is yellow and well sorted, but near the top of the formation the color grades to white and the degree of sorting decreases, with coarse grains of quartz distributed in the fine-grained sandstone.

The sandstone of the Entrada was formed as the result of eolian deposition in an arid environment, as indicated by the massive tangential crossbeds and locally frosted quartz grains. The upper portion of the Entrada shows evidence of reworking by water, the first evidence of the saline lakes which were to cover this area during deposition of the overlying Todilto Formation (Tanner, 1970).

Todilto Formation

The limestone and gypsum deposits of the Todilto Formation were named in 1917 by Gregory for exposures at Todilto Park in McKinley County, New Mexico. In the Regina area the Todilto gypsum is found as distinctive ridge-forming, hummocky outcrops which lack sedimentary structures. It is estimated to be between 30-50 m (100 and 150 ft) thick, and has a sharp contact with the underlying Entrada Formation.
The base of the Todilto is composed of approximately 8 ft (2.4 m) of thinly laminated, crenulated, petrolierous, gray-brown limestone, locally containing organic and clastic-rich layers. This grades up into a transition zone of laminated limestone with interbedded nodules of gypsum. Anderson and Kirkland (1960) attributed this structure to reorganization subsequent to deposition. The major lithology is massive, recrystallized gypsum which overlies the transition zone, reaching a maximum thickness of 40 m (130 ft) (Fig. 11).

The Todilto Formation was deposited in a saline lake under arid to semi-arid conditions during a tectonically stable period. Anderson and Kirkland (1960) estimated that the Todilto was deposited over a 20,000 year time span.

Morrison Formation

In the Regina quadrangle the Morrison Formation has four members; however, the Morrison was mapped as one unit. The members, in ascending order are the Recapture, the Westwater Canyon, the Brushy Basin, and the Jackpile. These names were introduced by Harshbarger and others (1951), with the exception of the Jackpile, which was named for exposures in the Laguna district, New Mexico (Moench and Schlee, 1967). The term Jackpile is not a formal member name, although it is widely used in northwestern New Mexico.

The interbedded sandstone and shale of the Morrison Formation was named by Eldridge and others in 1896 and the type section is located
Figure 11. White hummocky Todilto outcrops (Jt) and red, fine-grained sandstone of the Recapture Member of the Morrison Formation (Jm), offset by the Nacimiento fault and Faults 2A and 3A. Fault 2A is an antithetic fault that results in the repetition of the Entrada and Todilto Formations. Fault 3A is a cross fault that offsets the Nacimiento fault.
near Morrison, Colorado. It is approximately 230–250 m (750–800 ft) thick in the Regina quadrangle and the upper members form a continuous hogback or fin in the north and north-central portion of the area. The Morrison forms a sharp contact with the underlying Todilto Formation.

The Recapture, the lowest member of the Morrison Formation, is composed of interlayered, thin- to medium-bedded maroon-brown sandstone, siltstone and shale (Fig. 11). These units are typically poorly cemented and where exposures are good, small-scale badlands topography is developed. The sandstone in the Recapture is fine grained, rounded, poorly to moderately sorted, and contains abundant feldspar and mafic grains. It forms beds ranging in thickness from 1.3 cm to 0.6 m, weathers buff-pink, and is more abundant in the lower portion of the Recapture Member.

The overlying Westwater Canyon Member of the Morrison Formation is in sharp contact with the Recapture and consists of approximately 10 m (30 ft) of medium- to thick-bedded, moderately well sorted, rounded, feldspathic, olive-tan sandstone with thin interbeds of green shale. The sandstone is better indurated and coarser grained that that in the Recapture and typically forms a ledge or ridge. The shale that is typically found in the Westwater at other localities (Woodward and Schumacher, 1973a), could not be distinguished in the Regina quadrangle, so only the dominant sandstone was included in this member.

The Brushy Basin Member is in gradational contact with the Westwater Canyon and is primarily green-blue and gray shale and mudstone.
Thin- to medium-bedded, medium- to coarse-grained sandstone layers, nodular limestone and thin-bedded, silicified, reddish mudstone is also present. This member is approximately 140 m (450 ft) thick in the Regina quadrangle.

The Jackpile overlies the Brushy Basin Member and locally is transitional with it. The sandstone in this member characteristically forms rounded outcrops with cavities in the sides, and ranges in thickness from 15 to 30 m (50 to 100 ft), thinning to the south. At the northern exposures in the Regina quadrangle the Jackpile consists of thick-bedded conglomeratic sandstone layers with interbeds of green and gray shale up to 3 m (10 ft) thick. Farther south the thickness of both the sandstone and shale decreases.

The Jackpile sandstone is medium to very coarse grained, poorly sorted and moderately rounded, ranging from white to pink, buff and gray. It is composed of quartz and feldspar grains, pebbles of quartz and kaolinite up to 2.5 cm in diameter (Fig. 12) and grains of an unidentified green mineral, all of which have been cemented by silica and kaolinite in varying amounts. Large-scale trough cross-beds are characteristic and clasts of kaolinite are found outlining foreset beds. Although carbonaceous material is reportedly absent in the Jackpile, at one location a small pocket of carbonaceous material was found.

The contact with the overlying Cretaceous Dakota Formation is placed at the stratigraphically lowest occurrence of a thin-bedded,
dark grey, conglomeratic shale layers about 30 cm (1.0 ft) thick (Fig. 12). The b a (30 ft) of green shale that Albers (1972) recognized at the top of the horizon was not present in the region quadrangle. This discrepancy is due to the transformation at the base of the Dakota Formation into a red, conglomeratic sandstone. Repeated exposure of the Dakota Formation on the Grosse Crique branch has indicated that it is a marine deposit of the Lower Cretaceous period. The Dakota Formation crops out as a continuous ridge for almost the entire length of the region quadrangle and is about 400 ft (122 m) wide, as shown in Figure 12. Kaolinite clasts (white) and pebbles (dark) in the conglomeratic portion of the Jackpile Member of the Jurassic Morrison Formation.

Figure 12. Kaolinite clasts (white) and pebbles (dark) in the conglomeratic portion of the Jackpile Member of the Jurassic Morrison Formation.
dark gray, carbonaceous shale layer about 30 cm (1.0 ft) thick (Fig. 13). The 5 m (15 ft) of green shale that Gibson (1975) recognized at the top of the Morrison was not present in the Regina quadrangle. This discrepancy is due to the unconformity at the base of the Dakota.

The Morrison Formation was deposited in a continental fluviatile environment. The fine-grained sandstone of the Recapture was deposited in a braided or low sinuosity stream environment and the shale in the associated floodplain. The Westwater is the result of deposition in a north to northeast flowing braided stream. The Brushy Basin is dominantly due to deposition in a floodplain, and the sandstones represent deposition in strongly meandering streams. The sandstone of the Jackpile was deposited in an east flowing braided stream (Flesch, 1974).

Cretaceous System

Dakota Formation

The Dakota Formation crops out as a continuous ridge for almost the entire length of the Regina quadrangle and is about 40 m (125 ft) thick. It was named for exposures in Dakota County, Nebraska by Meek and Hayden in 1861. In the San Juan Basin the Dakota is latest Early Cretaceous and earliest Late Cretaceous in age (Grant and Owen, 1974).

Along the Nacimiento uplift the Dakota Formation is composed of three distinct lithologic units, a lower sandstone, a shale unit, and an upper sandstone. The lower sandstone is buff, orange and brown, medium grained, thin to medium bedded and cross-bedded, and has thin
Figure 13. Gray, carbonaceous shale at the contact between the Jurassic Morrison Formation (right) and the Cretaceous Dakota Formation (left).
interlaminations of fissile, black, carbonaceous shale. Iron concretions which stain the surrounding sandstone rust-colored, and kaolinite cement are locally present.

Above the lower sandstone is a layer of dark-gray carbonaceous shale about 10 m (30 ft) thick. Beds of sandstone 60-90 cm (2-3 ft) thick are present in the shale, locally showing planar cross-beds. Toward the top of this shale unit sandstone layers become thicker, forming a transitional contact with the overlying sandstone.

The upper sandstone is yellow-tan, fine grained, moderately well sorted, thin to medium bedded and contains thin laminations of black shale. It is approximately 12 m (40 ft) thick.

The Dakota Formation rests disconformably on the underlying Jurassic Morrison Formation, with gray carbonaceous sandstone and shale in contact with the Jackpile (Fig. 13). In comparison with the Jackpile, the sandstone of the Dakota forms darker, more angular outcrops and is finer grained, better sorted, and non-arkosic.

The deposits of the Dakota Formation represent a complex transition from continental alluvial plain deposits to shallow marine deposits. The lower sandstone was formed in meandering or braided stream environments; the interbedded shales representing overbank deposits. The middle shale is low coastline paludal, paralic and floodplain deposits, and the upper sandstone is the result of strandline and shallow marine deposition (Grant and Owen, 1974).
Mancos Shale

The Mancos Shale was named by Cross (1894) for exposures at Mancos, Colorado. The Mancos has been subdivided into several members in the San Juan Basin, but due to poor exposures the Mancos was mapped as one unit. In the Regina quadrangle this unit is about 600 m (2,000 ft) thick and in the north forms a broad valley cut by several low hogbacks. In the south part of the area the Mancos has been tectonically thinned and is a slope-forming unit. The basal contact is defined as the top of the highest major sandstone of the Dakota.

The major lithology in the offshore marine deposits of the Mancos is dark gray and black shale. The lower portion of the Mancos contains thin-bedded, fine-grained sandstone, thin beds of limestone, and locally lenses of broken fossil material with calcareous cement. In the middle of the Mancos a continuous fine-grained calcareous sandstone unit 1.5 m (5 ft) thick is exposed. This sandstone is made up of beds less than 2.5 cm thick with interbedded gray to brown shale. Thin beds of finely crystalline limestone and limestone concretions up to 15 cm in diameter are also present. The upper portion of the Mancos is characterized by numerous fossiliferous septarian concretions up to 1 m (3 ft) in diameter which occur along two or three main stratigraphic horizons. A continuous gray limestone bed 0.6 m (2 ft) thick is also present. Near the contact with the overlying Mesaverde, sandstone similar to that found in the Mesaverde is present, evidence of the transitional and intertonguing relationship between the Mancos and the Mesaverde.
Mesaverde Group

The Mesaverde Group was named for exposures at Mesa Verde, Colorado by Holmes (1877). In the Regina quadrangle it forms a prominent hogback in the north, and can be subdivided, in ascending order, into the Point Lookout Sandstone, the Menefee Formation, and the La Ventana Tongue of the Cliff House Formation (Fig. 14).

The Point Lookout Sandstone is composed of tan, fine-grained, moderately well-sorted, slightly micaceous, medium-bededed quartz sandstone with a calcareous or kaolinitic (?) matrix. Small flecks of biotite (?) give the rock a salt and pepper appearance. The Point Lookout Sandstone conformably overlies the Mancos, and thin beds of gray shale occur in the lower Point Lookout.

The major constituent of the Menefee Formation is gray-black shale with interbedded medium- to coarse-grained, thin-bededded, moderately sorted, carbonaceous sandstone layers 0.6–1.0 m (2–3 ft) thick. Also present are layers of coal and carbonaceous shale (Fig. 15) and lenses of ironstone that may show oolitic textures.

The La Ventana Tongue of the Cliff House Sandstone overlies the Menefee Formation. It consists of tan, olive-green and locally brick-red sandstone that is medium grained, moderately well sorted and locally kaolinitic. The La Ventana Tongue has the same general salt and pepper appearance as the Point Lookout Sandstone.

The Point Lookout Sandstone is a regressive coastal-barrier sandstone that was deposited during marine regression to the northeast.
Figure 14. Northern Regina quadrangle; hogbacks formed on prominent sandstone in the Mancos Shale (Km), Point Lookout Sandstone, and La Ventana Tongue of the Cliff House Formation (Kmv). Lewis Shale (Kl) is a valley former and Ojo Alamo Sandstone (Toa) forms outcrop in the northwest corner of the photograph.
Figure 15. Gray-black coal-bearing shale and carbonaceous sandstone of the Menefee Formation overlain by the sandstone of the La Ventana Tongue of the Cliff House Formation; Cretaceous Mesaverde Group (Kmv).
The Menefee Formation was deposited in nonmarine paludal to alluvial plain environments, and the La Ventana Tongue is a transgressive sandstone that formed when the onlapping Cretaceous sea stalled during transgression (Molenaar, 1977).

The thickness of the Mesaverde Group varies along the east-central San Juan Basin, and shows a general thickening to the south and west. In the Regina quadrangle the Mesaverde is about 150 m (500 ft) thick, but to the south, by La Ventana, the Mesaverde is over 550 m (1,800 ft) thick.

Lewis Shale

The Lewis Shale conformably overlies the Mesaverde Group and was named by Cross, Spencer and Purington (1899) for exposures near Ft. Lewis, Colorado. Along the northwest side of the Nacimiento uplift the Lewis is composed of 460 m (1,500 ft) of gray, brown and black shale that closely resembles the Mancos Shale. Thin beds of fine-grained sandstone and limestone are interbedded with the shale and stratigraphic horizons with abundant gray-brown fossiliferous limestone concretions are also present.

The Lewis is in conformable contact with the underlying Mesaverde Group, and is the result of deposition farther offshore than the nearshore marine facies of the La Ventana Sandstone (Fassett, 1974).
The type sections of the Kirtland Formation and Fruitland Shale are in the northwest San Juan Basin along the San Juan River, where Bauer (1916) first identified them as two distinct lithologic units. The Fruitland Formation is non-marine lower coastal plain deposits and contains numerous thick coal beds. The Kirtland Shale is the result of upper coastal plain and alluvial fan deposition and although it is similar in appearance to the Fruitland, it generally lacks major coal beds and has distinct thick fluvial sandstone beds. These formations both decrease in thickness to the east, away from the type sections, and along the eastern margin of the San Juan Basin they are typically mapped as one unit due to this thinning and to truncation prior to deposition of the Ojo Alamo Formation (Molenaar, 1977). This area was a shallow embayment of the Cretaceous sea, and an erosional unconformity between the Kirtland and the Fruitland along the eastern margin of the San Juan Basin is the first direct evidence of Laramide uplift in this area (Baltz, 1967).

The slope-forming Kirtland and Fruitland unconformably overlies the Lewis Shale, and is composed of black, gray and olive drab carbonaceous shale and light gray to buff, fine- to very coarse-grained, poorly sorted sandstone. Silicified wood fragments are common, and are useful for distinguishing the Kirtland and Fruitland from the underlying Lewis Shale. The thickness of the Kirtland and Fruitland is estimated to be 30 m (100 ft), but the location of the contact with the Lewis is imprecise, and this is an approximate thickness only.
The Paleocene Ojo Alamo Formation unconformably overlies the Kirtland and Fruitland, and is 30-40 m (100-125 ft) thick in the Regina quadrangle. It was named by Brown (1910) for exposures in the southwest part of the San Juan Basin.

The Ojo Alamo is poorly exposed in most of the Regina quadrangle, but forms a resistant fin in the SW 1/4, SW 1/4, sec. 11, T. 23 N., R. 1 W. (Fig. 14). The Ojo Alamo is tan-gray to rust-orange, thick-bedded, cross-bedded, locally conglomeratic sandstone with thin interbeds of olive-drab shale. The sandstone is very poorly sorted and contains feldspar, mafic grains, mica, kaolinite and hematite cement in varying proportions. Fossil logs are common.

The Ojo Alamo was deposited by sediment-laden streams draining into the San Juan Basin (Balts, 1967).

The Paleocene Nacimiento Formation was named in 1910 by Gardner for exposures in the vicinity of Cuba, New Mexico (then called Nacimiento). The Nacimiento conformably overlies the Ojo Alamo Formation and is composed of 300 m (1,000 ft) of olive-green and gray carbonaceous shale with interbeds of tan, fine- to coarse-grained, poorly cemented, arkosic and argillaceous sandstone.

As composed of a basic sandstone with overlying gray, yellow, purple...
Baltz (1967) reported that the Nacimiento was deposited during subsidence of the San Juan Basin, when sediment-laden streams formed a coalescing alluvial fan as they drained into the swampy basin. The Nacimiento represents terrestrial, floodplain, ephemeral lake and stream channel deposits.

San Jose Formation

Simpson (1948) proposed that the name San Jose Formation replace the previously used term Wasatch Formation to apply to the Eocene pastel shales and buff sandstone exposed along the eastern margin of the San Juan Basin. The type section of the San Jose Formation is 1.6 km (1 mi) northwest of the town of Regina.

Baltz (1967), in his stratigraphic and tectonic study of the eastern San Juan Basin, divided the San Jose into four members (in ascending order): the Cuba Mesa Member, the Regina Member, the Llaves Member and the Tapicitos Member. Most workers in this area, including myself, have been unable to distinguish these members and have mapped the San Jose as one unit.

The upper contact of the San Jose is not exposed in the map area, but to the south in the Cuba quadrangle the San Jose is 250-430 m (800 to 1,400 ft) thick (Woodward and others, 1972a). The San Jose Formation rests unconformably on the Nacimiento Formation and to the east, toward the uplift, up to 300 m (1,000 ft) of upper Nacimiento strata were eroded prior to deposition of the San Jose. The San Jose is composed of a basal sandstone with overlying gray, yellow, purple,
and green shale and interbedded conglomeratic sandstone (Fig. 16). 
The basal sandstone is medium to very coarse grained, cross-bedded, 
and contains mica flakes, mafic and feldspar grains, and locally 
concentrations of limestone cobbles up to 10 cm in diameter (Fig. 17). 
The San Jose is the result of continental deposition and represents 
flood plain and stream channel deposits (Baltz, 1967).

Tertiary - Quaternary Deposits

Older Alluvium

In the west-central portion of the area clay, sand, and gravel are 
found at the heads and along the sides of valleys at higher levels 
than the younger Quaternary alluvium. This older alluvium was incised 
and eroded during Recent time, possibly due to lowering of the base 
level since the time of its deposition.

The older alluvium forms flat, sage covered areas between ridges 
and often lacks active stream channels. It is difficult to estimate 
the thickness, but it is probably less than 15 m (50 ft), except along 
San Jose Creek where it may be up to 30 m (100 ft) thick.

Pediment Deposits

Pediment deposits cap ridges in the west-central to southwestern 
portions of the area. These deposits are composed of gravel with 
minor clay and sand, all of which has been derived from Precambrian, 
Paleozoic, or Mesozoic rocks. Pediment deposits are typically composed
Figure 16. Pastel shales of the San Jose Formation (Ts}. Note change in regional dip from approximately 65° to nearly horizontal.
Figure 17. Conglomerate in the Eocene San Jose Formation, cobbles are limestone, probably derived from Cretaceous rocks.
of a combination of Precambrian clasts, and clasts of the rock type found adjacent to the deposit directly to the east (i.e., upslope, toward the source). The pediment gravels in the Regina quadrangle range in thickness from 0 to 15 m (0 to 50 ft).

Quaternary Deposits

Landslide Deposits

Unsorted angular debris derived from the Dakota Formation is found in piles along the base of some Dakota hogbacks. These deposits were formed when uplift and tilting of the Mesozoic section, and subsequent erosion of the nonresistant Mancos Shale resulted in an unstable slope on the Dakota Formation, causing landslides. Generally it is the middle shale and upper sandstone that have moved downslope, but at one location (sec. 23, T. 23 N., R. 1 W.) the entire formation has been involved in sliding. These deposits range in thickness from 0-20 m (0 to 75 ft).

Alluvium

Alluvial clay, silt, and sand deposits up to approximately 40 m (125 ft) in thickness fill valleys in the Regina quadrangle. This material is the result of Recent alluvial processes, and is typically vegetated only by grasses. Also included in this unit is minor colluvial material adjacent to stream valleys.
REGIONAL TECTONIC SETTING

There are two principle tectonic features in the eastern half of the Regina quadrangle, the San Juan Basin and the Nacimiento uplift. The Gallina-Archuleta arch is adjacent to the Nacimiento uplift and is to the northeast of the Regina quadrangle (Fig. 18). The San Juan Basin and the Gallina-Archuleta arch are part of the Colorado Plateau Province (Kelley, 1950), and the Nacimiento uplift is part of the Rocky Mountain foreland (Woodward, 1976). These tectonic features were formed during Laramide time when the Colorado Plateau was shifted northeastward against the Rocky Mountain foreland, and the Nacimiento uplift rose with respect to the adjacent San Juan basin (Kelley, 1955b). Further modification of the Nacimiento uplift in the form of vertical deformation occurred later in the Tertiary, during formation of the Rio Grande rift (Woodward and others, 1972b).

The San Juan Basin is a slightly oval-shaped, strongly asymmetric basin that measures approximately 290 km (180 mi) north-south and 215 km (135 mi) east-west. This arcuate basin has an axis which is strongly convex to the north, and the northern and eastern edges dip much more steeply than the south. The San Juan Basin is bounded on the east by the monocline of the Gallina-Archuleta arch, and the reverse faults and overturned synclinal bend of the Nacimiento uplift. There is approximately 4,000 m (13,000 ft) of structural relief between the Gallina-Archuleta arch and the adjacent part of the San Juan Basin, and approximately 3,000 m (10,000 ft) of structural relief between
Figure 18. Generalized tectonic map, northwest New Mexico. Map shows location of the eastern part of the Regina quadrangle (red) and area of tectonic map, Figure 3 (blue) (modified from Woodward and Callender, 1977a).
the highest part of the Nacimiento uplift and the adjacent San Juan Basin (Woodward and Callender, 1977a)

The Nacimiento uplift trends north and is approximately 80 km (50 mi) long and 10-16 km (6 to 10 mi) wide. It consists of a series of uplifted, east-tilted Precambrian blocks with local Paleozoic sediments. The western margin of the Nacimiento uplift is a monocline with a broad anticlinal bend and a sharp synclinal bend (Kelley, 1955a). This monocline has been cut by the Nacimiento fault in the north and by the Pajarito fault in the south. The Nacimiento fault has the form of an upthrust, which dips steeply to the east at depth, but flattens upward, locally yielding westward over the San Juan Basin for distances up to 760 m (2,500 ft) (Woodward and others, 1972b).

At the north end the Nacimiento uplift has a broad faulted anticline that plunges 10° to 20° north and merges with the Gallina-Archuleta arch. The eastern margin of the uplift dips gently east and is covered by the onlapping volcanics of the Jemez field.

The Gallina-Archuleta arch is a north- to northwest-trending arcuate anticlinorium approximately 130 km (80 mi) long and 25-30 km (15 to 20 mi) wide. It is a complex belt of open folds and high angle normal faults that is bounded on the west by a west-dipping monocline. The Gallina-Archuleta arch separates the relatively deep San Juan Basin from the structurally shallow Chama Basin.
STRUCTURES IN THE REGINA QUADRANGLE

In the eastern half of the Regina quadrangle the major tectonic features are the northwestern part of the Nacimiento uplift, represented by a fault-bounded uplifted block of Precambrian crystalline rocks and Paleozoic and Mesozoic sedimentary rocks, and a part of the eastern margin of the San Juan Basin, represented by a series of upturned and locally overturned sedimentary rocks ranging in age from Jurassic to Tertiary.

Nacimiento Uplift

The western limb of the north-plunging anticline at the north end of the Nacimiento uplift is present along the eastern side of the Regina quadrangle. Precambrian igneous and metamorphic rocks are unconformably overlain by Paleozoic and Mesozoic sedimentary rocks that dip to the north and northeast, and locally to the west. The Nacimiento fault is the main feature along the northern Nacimiento uplift. Antithetic and synthetic faults are present parallel to the main fault, and high-angle faults are oblique to the main fault, commonly offsetting it.

The Nacimiento fault is an east-dipping, high-angle reverse fault that trends north through most of the Regina quadrangle, veering to the northeast at its most northern exposures. The fault is fairly well exposed in the north where units on either side of the fault are in sharp contact. To the south the fault trace is typically covered with pediment deposits, and its location is approximate in some instances. The angle
of dip of the Nacimiento fault is difficult to measure directly in this area. Hurson (1958) reported that the fault dips 83° east in sec. 24, T. 23 N., R. 1 E. This information in conjunction with the straight trace indicates that the Nacimiento fault dips very steeply east throughout the Regina quadrangle. L. A. Woodward (pers. comm., 1980) reported that the Nacimiento fault dips approximately 45° east a few miles south of this area, and Anderson (1970) classified the fault as an upthrust in his report on the western margin of the Nacimiento uplift. I saw no indications of overthrusting along the fault in the Regina quadrangle, and have therefore classified it as high-angle reverse. This discrepancy may be explained in two ways:

1. The fault is an upthrust but has been eroded to deeper structural levels and therefore has the form of a high-angle reverse fault.

2. Upthrusting and associated horizontal movement never occurred in the Regina quadrangle.

The stratigraphic separation along the Nacimiento fault is variable, reaching a minimum of 900 m (3,000 ft) in secs. 11, 14, T. 33 N., R. 1 W., where the Cretaceous Mancos Shale is in contact with Precambrian rocks. The separation decreases both north and south of this area and is approximately 430 m (1,400 ft) at the southern border and 300 m (1,000 ft) at the eastern border. The slip that has occurred along the fault is greater that the stratigraphic separation, due to the steep attitude of the beds. The minimum structural relief between the Nacimiento uplift and the San Juan Basin in the Regina quadrangle is 3,400 m (11,000 ft).
Woodward and others (1972b, p. 2386), in reference to the upthrust nature of the Nacimiento fault, stated that "the fault tends to be steep where there is little stratigraphic separation, but dips more gently where there is greater displacement." In the Regina quadrangle the observed 900 m of stratigraphic separation, and the steeply dipping nature of the fault seems to support the hypothesis that the Nacimiento fault here did have the configuration of an upthrust.

In the southern part of the area the Nacimiento fault is composed of two en echelon faults which parallel each other for about 1.5 km (1 mi). The western fault (1A) is the main Nacimiento fault to the south, in the Cuba quadrangle, but the amount of stratigraphic separation decreases northward, and it may merge with the eastern fault, which is the main Nacimiento fault to the north. The exact relationship between these two faults is in question due to the fact that the area where they would meet is covered by pediment deposits. The eastern fault, although poorly exposed, appears to be hinged about 1.2 km (0.75 mi) to the south of the area, where Abo Formation is faulted against Precambrian. This fault cuts abruptly upsection, showing 300 m (1,000 ft) of stratigraphic separation at the southern border of the area, and 900 m (3,000 ft) of separation 2.4 km (1.5 mi) north.

A synthetic fault (i.e., a fault with the same general attitude and sense of displacement as the Nacimiento fault) is present in the Regina quadrangle in sec. 18, T. 23 N., R. 1 E. This fault (1B) has approximately 45 m (150 ft) of stratigraphic separation, with Mancos Shale in fault contact with Dakota Formation. This fault is poorly
exposed along the gentle dip-slope of the Dakota hogback and its attitude could not be determined. Work by Gibson (1975) indicates that Fault 1B becomes the main Nacimiento fault to the northeast.

An antithetic fault (i.e., a fault that has moved in opposition to the general uplift) is present in sec. 24, T. 23 N., R. 1 W., and has approximately 150 m (500 ft) of stratigraphic separation, resulting in the repetition of the Entrada, Todilto, Morrison and Dakota Formations in this area. This fault (2A) dips steeply to the east and is located on the west side of the Nacimiento fault, merging with it along strike (Fig. 11).

A number of high-angle faults that are oblique or perpendicular to the Nacimiento fault are present along its length. These faults can be divided into two groups; faults that offset the Nacimiento fault (3A, 3B, 3C), and faults that terminate against the Nacimiento fault (4A, 4B, 4C, 4D).

There are three faults that offset the Nacimiento fault; Fault 3A in sec. 24, T. 23 N., R. 1 W., Fault 3B at Mahan Canyon and Fault 3C near San Jose Creek (Figs. 1, 11, 19). All three of these faults show components of both dip slip and strike slip, as nearly vertical beds are offset. In all cases the separation is down to the north, with right separation and probably right slip. These faults are all about 800 m (2,500 ft) in length, and the stratigraphic separation increases to the east, toward the Nacimiento fault, reaching a maximum of 300 m (1,000 ft). To the west or northwest these faults die out in the
Figure 19. Geology at Mahan Canyon, looking north. Nacimiento Fault (NF) and prominent Todilto outcrops show offset by Fault 3B. Madera and Abo Formations (TPm and Pa) are on the east side of main fault.
incompetent shale of the Mancos Shale or Morrison Formation and to the
east Faults 3B and 3C terminate at the Nacimiento fault while Fault 3A
extends a short distance beyond the main fault.

This set of faults in part causes the sharp eastward bend in the
Nacimiento fault, as well as decreases the amount of displacement that
occurs along the northern termination of the uplift.

In the east-central Regina quadrangle, high-angle faults terminate
against the Nacimiento fault. Faults 4A, 4B, 4C, and 4D trend northwest
to west and Fault 4C extends into the Gallina quadrangle, connecting
with the Dove Creek fault, as mapped by Gibson (1975). It is this fault,
as well as Fault 4D, to the south, that Wood and Northrop (1946),
Hutson (1958) and Baltz (1967) have mapped as the San Pedro Mountain
fault. This fault was described as an east-trending, oblique-slip
fault that is down to the north, showing 900-1,200 m (3,000 to 4,000 ft)
of displacement. There is no fault that fits this description in the
Regina quadrangle.

In a sense, these northwest- to west-trending faults are antithetic
with respect to the plunging anticline that forms the northern termination
of the Nacimiento uplift, as the downdropped side of all of them is to
the south. The maximum stratigraphic separation is 120 m (400 ft) and
results in the repetition of the Arroyo Peñasco and lower Madera
Formations, except at Fault 4D, where Abo Formation is faulted against
Precambrian rocks.

Small faults in the hanging wall of the Nacimiento fault are
present in the Precambrian, Arroyo Peñasco, Madera and Abo Formations.
These faults appear to be extensional features and are the result of stretching across the plunging anticline. Stratigraphic separation is minimal in comparison with other faults present, ranging from 15-30 m (50 to 100 ft). Fault 5A must be a reactivated pre-Madera - post-Arroyo Peñasco fault, as the Arroyo Peñasco appears to be missing from beneath the Madera on the east side of the fault, although it should be noted that poor exposures in this area hampered identification of units and structural interpretation.

San Juan Basin

The major structural feature associated with the San Juan Basin is the steeply dipping to overturned limb of the asymmetric synclinal bend along its eastern margin. The Morrison and Dakota Formations are overturned as much as 60° along the Nacimiento fault, and the dip increases to vertical to the west, and then gradually becomes nearly horizontal along the western margin of the area, over a distance of about 4.0 km (2.5 mi).

The northern part of the area is characterized by a series of steeply dipping hogbacks that trend north to northeast, forming a broad, open, northwest-plunging anticline. Two small, poorly exposed, high-angle faults with less than 15 m (50 ft) of stratigraphic separation are present in this hogback belt. The faults cut across the hogbacks, causing right separation in one case, and left separation in the other (Fig. 14). These faults, as well as the open anticline, probably formed
in response to arching of the anticline at the northern termination of the uplift, which in turn is related to the bend in the Nacimiento fault.

An antithetic fault is present in the San Jose Formation in sec. 3, T. 22 N., R. 1 W. This high-angle fault shows approximately 8 m (25 ft) of separation and can be traced for less than 800 m (2,500 ft) before being covered by the alluvium along San Jose Creek.
STRUCTURAL ANALYSIS

Paleozoic Events

The area that is now the Nacimiento uplift was structurally high during the late Paleozoic and was a southern extension of the Uncompagre Highland (Kelley, 1955b). During Late Mississippian or Early Pennsylvanian time this north-trending feature, the Peñasco axis, was uplifted and Mississippian strata were mostly eroded, although some Mississippian rocks are preserved in downfaulted blocks (Fitzsimmons and others, 1956).

The overstepping, onlapping nature of the Pennsylvanian Osha Canyon and Sandia Formations, the lower and upper members of the Madera Formation, and the Permian Abo Formation indicate that the Peñasco axis was asymmetric with the north end higher than the south end. Martinez (1974) suggested that an increase in the conglomeratic arkosic component in the Madera Formation to the west implied that the uplift was steeper on the west side than the east side. The absence of the Madera along the western margin of the Nacimiento uplift, and its presence in the Regina quadrangle, indicates that the axis was never completely covered by Pennsylvanian seas, and that the northern extent of the uplift was in the vicinity of the east-central Regina quadrangle. By Late Permian time the Peñasco axis no longer acted as a source of sediment.

Late Cretaceous and Tertiary Events

The Nacimiento uplift formed in response to several stress regimes during Late Cretaceous and Tertiary time. It is the product of both
compressional Laramide deformation and extensional Rio Grande rift-related deformation, both of which tended to increase the structural relief between the uplift and the San Juan Basin.

The location of the present uplift seems to be controlled by a pre-uplift area of structural weakness. The area that is now the Nacimiento uplift was once the Peñasco axis. This repetition of positive and negative tectonic features over long periods of time is not unusual and has been noted by Baltz (1967) in the Colorado Plateau and by Hills (1972) in both Africa and Australia.

Laramide deformation along the Nacimiento uplift began during Late Cretaceous time. A slight unconformity in the Kirtland Shale and Fruitland Formation is the first evidence seen in the Regina quadrangle. In addition, the coal beds which are so diagnostic of the Kirtland-Fruitland in the central San Juan Basin thin toward the Nacimiento uplift and are absent in the Regina quadrangle (Baltz, 1967).

During the Laramide orogeny, northeastward shift of the Colorado Plateau (Kelley, 1955b) produced a primary compressional stress field and resulted in a right-shift force couple as the San Juan Basin was shifted against the Rocky Mountain foreland. This right-lateral movement produced northwest trending, en echelon folds along the eastern margin of the San Juan Basin (Fig. 3). These en echelon folds may have formed in response to Riedel shearing of the basement (Hills, 1972).

The northwest-trending folds are well-exposed along the southern Nacimiento uplift, where the Nacimiento Formation is thin at the crests of the anticlines (Baltz, 1967; Woodward and others, 1972b). The Eocene
San Jose Formation rests unconformably on the Paleocene Nacimiento Formation and is itself folded, indicating continued development of the folds. In the Regina quadrangle these en echelon folds are evident in the subsurface only (Baltz, 1967).

Laramide deformation in this area is characterized by minor shortening associated with basin subsidence and primarily vertical deformation. As this deformation progressed, closely spaced, north-trending vertical fractures formed in the basement rocks and subsequent shear folding produced drape folds, and a monocline developed in the overlying incompetent strata (Woodward and others, 1972b) (Fig. 20). This type of deformation is typical of that found elsewhere in the Colorado Plateau where monoclines are the major structural feature along which most of the deformation has occurred (Kelley, 1955a). Early development of the monocline was probably synchronous with the last stages of en echelon folding (Woodward and others, 1972b), and formation of the monocline may have been accompanied by at least some vertical faulting.

Deformation along the monocline that bounded the Nacimiento uplift took the form of stretching of the folded strata, concentric shearing, and antithetic and synthetic faulting along longitudinal normal faults (Baltz, 1967). Evidence for longitudinal normal faulting along the crest of the Nacimiento uplift is documented by Gibson (1975) and DuChene (1973). A major portion of the 3,400 m (11,000 ft) of structural relief present along the Nacimiento uplift is the result of
Figure 20. Diagrammatic structure sections showing development of the range-marginal structures in the eastern Regina quadrangle. A, after deposition of the Paleocene Nacimiento Formation (Tn); B, after deposition of the Eocene San Jose Formation (Tsj); C, prior to faulting; D, after faulting (after Woodward and others, 1972b).
deformation due to monocline formation. A minimum of 3,050 m of structural relief was developed on the Nacimiento uplift prior to deposition of the Pedernal Chert on the Precambrian rocks in the northern Nacimiento Mountains (Timmer, 1976). The Pedernal Chert is a part of the Abiquiu Formation of probable Late Oligocene-Early Miocene age (Vazzana, 1980).

The unconformity between the Nacimiento and San Jose Formations becomes more angular to the east, indicating increased relative uplift along the major north-south trend during the late Paleocene. Uplift along the monocline occurred primarily during and after deposition of the Eocene San Jose Formation. Evidence indicates that the development of the monocline was episodic. The unconformity between the lower and middle part of the San Jose just to the south of the Regina quadrangle indicates that some uplift occurred early in San Jose time and was followed by a period of local quiescence. During this period of relative stability the middle beds of the San Jose transgressed over the previously folded upper Cretaceous and lower Tertiary strata. In the Regina quadrangle, there is no unconformity in the San Jose Formation, indicating that deformation along the monocline occurred principally after deposition in this area (Fig. 20).

During late Tertiary time, when final movement along the Nacimiento fault occurred, an extensional environment existed across northern New Mexico associated with the Rio Grande rift. This northwest-southeast extension could produce the same secondary stresses which existed during
during Laramide time (J. F. Callender, pers. comm., 1980) (Fig. 21). Uplift along the Nacimiento fault may also be the result of stresses developed in association with a proposed mantle bulge beneath the Rio Grande rift (Lipman, 1969; Keller, 1978). The westward and upward pushing of a mantle bulge could produce the forces that were responsible for some of the faulting.

In the Regina quadrangle the Nacimiento fault is a high-angle reverse fault that bends to the east, probably following the northern end of the Peñasco axis. This change to a northeasterly trend is accomplished by both bending of the fault and displacement along cross faults (Fig. 3). The shifting of movement along the Nacimiento uplift from one major fault plane to another, as is seen at both the north and south ends of the fault in the Regina quadrangle, could be due to basement configuration, or to continued episodic uplift which was centered at different points along the uplift at different times.

A convergent wrench system was present during faulting along the Nacimiento uplift (Baltz, 1967; Slack and Campbell, 1976). Convergent wrenching has a tendency to enhance compressive features such as reverse faults and thrusts. In addition, wrenching would create a "gap" where the Nacimiento fault bends to the east (Fig. 22). This extensional feature mimics the rhombochasm as described by Carey (1958), and is represented by the graben present between the Nacimiento fault and Fault 2A.

There is some disagreement over the timing of the faulting along the Nacimiento uplift. Baltz (1967, 1978) believed that faulting
Figure 21. Strain diagrams showing forces during Laramide time (A) and during Rio Grande rifting (B).

Figure 22. Wrench zone along the northwest Nacimiento uplift. Theoretical development of a "gap" where bend in fault is present (A). Actual feature seen the Regina quadrangle is a graben between the Nacimiento fault and fault 2A (B).
occurred during Eocene time, at the culmination of the Laramide orogeny. Kelley (1950), Woodward (1976) and Callender (pers. comm., 1980) all indicated that at least some faulting occurred in Neogene time in association with Rio Grande rift formation. Evidence for the younger timing include:

1. The Pedernal Chert Member of the Abiquiu Formation rests unconformably on Precambrian rocks in the northern Nacimiento Mountains and is 300 m (1,000 ft) higher in elevation than the Pedernal Chert at Cerro Pedernal (Lawrence, 1979), and dips slightly east (Timmer, 1976) indicating post-Abiquiu uplift.

2. The geometry of the upthrust farther south indicates that the most recent faulting is considerably younger than the monocline it cuts.
ECONOMIC GEOLOGY

Minerals of potential economic importance in the Regina quadrangle include copper, uranium, coal and gypsum. Although there is evidence of abundant prospecting activity in this area, and even reports of minor production, no deposit has proven to be of economic importance up to the present time.

Copper

Economic copper deposits are present along the western boundary of the Nacimiento uplift, east of the town of Cuba, New Mexico. These deposits are located in Permian and Triassic quartzose and arkosic sandstone, and are associated with carbonaceous material in permeable paleochannels. It is thought that these deposits were formed during Triassic time when copper sulfides were precipitated from groundwater due to reduction by carbonaceous material. Later oxidation resulted in halos of azurite, malachite and chrysocolla. More information regarding these deposits can be found in publications by Kaufman, Schumacher and Woodward (1972), Woodward and others (1974b), and Woodward, Kaufman and Schumacher (1974a).

In the Regina quadrangle copper mineralization is present in west-central sec. 1, T. 22 N., R. 1 W. in the Abo Formation, and in the NW 1/4 sec. 31, T. 23 N., R. 1 E. in the upper Madera Formation. At the prospect in the Abo, malachite is found in pale green to pale orange, arkosic, conglomeratic sandstone, as grain coatings, interstitial fillings,
and replacement of clay galls. Locally abundant biotite and grain coatings of black, carbonaceous material are also present at this prospect.

The prospect pit in the Madera Formation shows sparse malachite mineralization associated with tan, medium- to coarse-grained biotite-bearing arkosic sandstone. Woodward and others (1974b) report that mineralization in the Madera is the result of leaching of copper minerals from the overlying Abo Formation, which could account for the low-grade nature of this prospect.

Gibson (1975) cites lack of large paleochannels and carbonaceous material in the Abo Formation as reasons for the absence of economic copper mineralization along the northern Nacimiento uplift.

Uranium

Uranium mineralization is present in the Regina quadrangle in the Madera, Abo, and San Jose Formations. Brown (1955) was the first to investigate the uranium occurrences in the Madera and Abo Formations in this quadrangle. Santos and others (1975) reported that in 1956, 20 tons of ore assayed at 0.03 percent $U_{3}O_{8}$ and 0.06 percent of $V_{2}O_{5}$ was shipped from sec. 25, T. 23 N., R. 1 W., and that 4 tons of ore assayed at 0.08 percent $U_{3}O_{8}$ was shipped from sec. 30, T. 23 N., R. 1 E. in 1954. In addition, a few truckloads of ore were produced from a small mine in sec. 19, T. 23 N., R. 1 E. (Hutson, 1958). Chenoweth (1974), in his study of uranium occurrences in the Nacimiento-Jemez region,
mentions the deposits studied by Brown, and also reports an occurrence of possible meta-autunite in the mudstone of the San Jose Formation, north of Regina, New Mexico.

The uranium in these deposits is thought to have been derived from devitrification of the Bandelier Tuff. Subsequent mobilization by migrating groundwater transported it to permeable units where reduction and precipitation occurred (Chenoweth, 1974). Although this theory may be applicable for the occurrences east of the Nacimiento Mountains, it would not apply in the Regina quadrangle where the Nacimiento Mountains would have acted as a barrier to groundwater flow from the Jemez region.

Coal

Thin beds of coal and carbonaceous shale are present in the Menefee Formation of the Mesaverde Group. Although there is no published information on coal production in this area, numerous prospect pits in secs. 1, 11 and 12, T. 23 N., R. 1 W. and the evidence of recent excavations, suggest that a small-scale operation is presently under way. The thin discontinuous beds, poor quality, and steep dips of the coal in the Menefee would deter large-scale mining operations.

Gypsum

Gypsum deposits of the Todilto Formation are abundant in the Regina quadrangle and are up to 40 m (120 ft) in thickness. More easily accessible gypsum deposits elsewhere make these occurrences unattractive at this time.
REFERENCES


Kelley, V. C., 1955b, Regional Tectonics of the Colorado Plateau and relationship to the origin and distribution of uranium: Univ. New Mexico Publications in Geology, no. 5, 120 p.


Meek, F. B., and Hayden, F. V., 1861, Descriptions of new Lower Silurian (Primordial), Jurassic, Cretaceous, and Tertiary fossils, collected in Nebraska, by the exploring expedition under the command of Capt. Wm. F. Raynolds, U.S. Topographic Engineers; with some remarks on the rocks from which they were obtained: Philadelphia Academy of Natural Science Proceedings, v. 13, p. 415-447.


Molenaar, C. M., 1977, Stratigraphy and depositional history of the upper Cretaceous rocks of the San Juan Basin area, New Mexico and Colorado, with a note on economic resources: New Mexico Geological Society Guidebook, 28th Field Conference, San Juan Basin III, p. 159-166.


